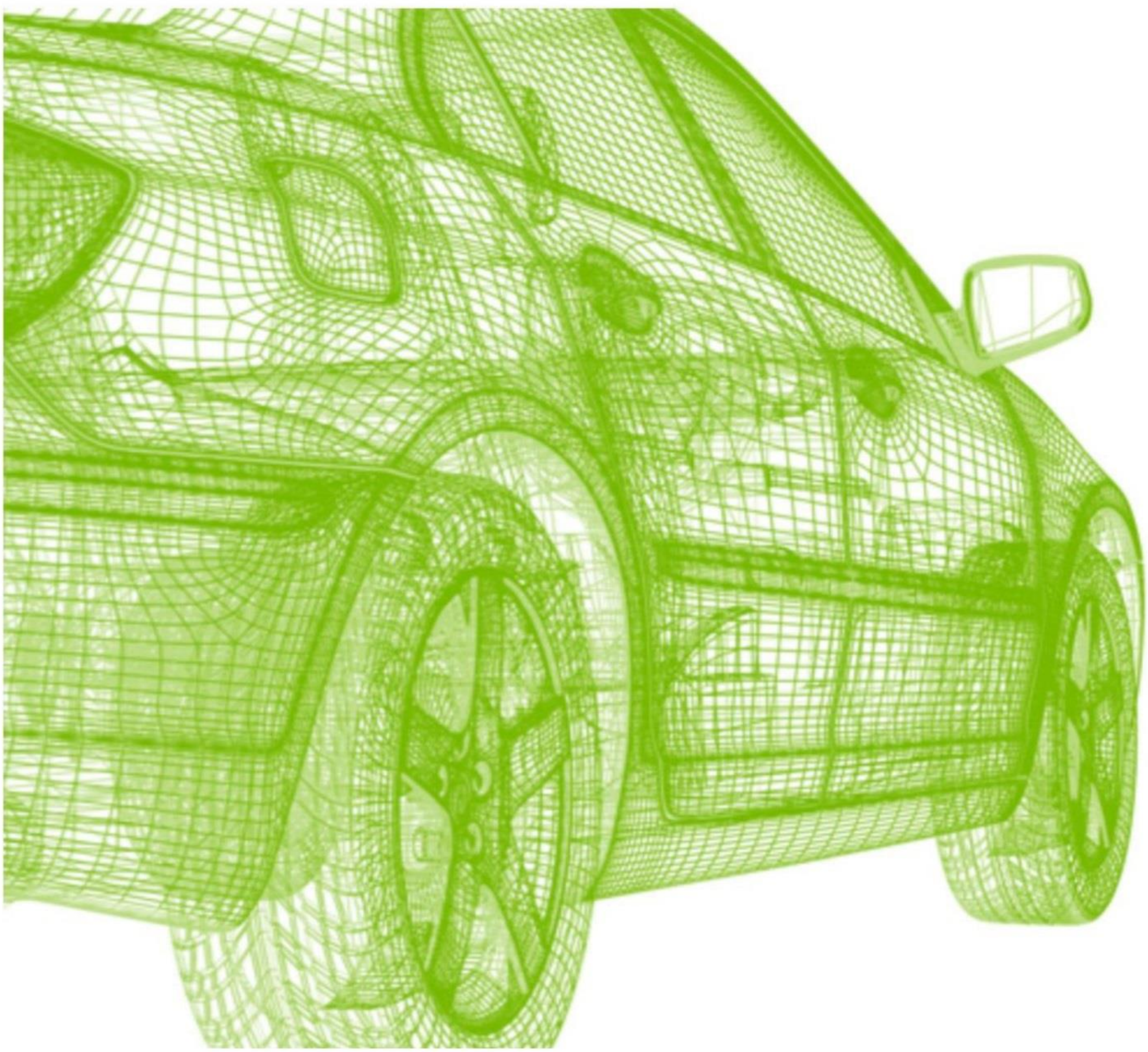
ANL/ESD-17/17

An Extensive Study on Sizing, Energy Consumption, and Cost of Advanced Vehicle Technologies

Energy Systems Division



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Energy Systems Division, Argonne National Laboratory

October 2018

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NOTATION

ACRONYMS AND ABBREVIATIONS

AER	all-electric range
Argonne	Argonne National Laboratory
APRF	Advanced Powertrain Research Facility
AU	Automatic Transmission
BEV	battery-powered electric vehicle
BEV100	BEV with 100 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
BEV200	BEV with 200 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
BEV300	BEV with 300 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
CAFE	Corporate Average Fuel Economy
CD	charge-depleting
CI	compression ignition
CNG	compressed natural gas
CO_2	carbon dioxide
CS	charge-sustaining
CSI	Civil Society Institute
DCT	dual-clutch transmission
DIRECT	Dividing Rectangles [algorithm]
DM	Discrete Manual Transmission
DOE	U.S. Department of Energy
DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
E85	blend of 85% ethanol and 15% gasoline by weight
EDV	electric drive vehicle
EIA	Energy Information Administration
EOL	end-of-life
EPA	U.S. Environmental Protection Agency
E-REV	extended-range electric vehicle
GHG	greenhouse gas
GPRA	Government Performance and Results Act
GVW	gross vehicle weight
GGE	gasoline gallon equivalent
HEV	hybrid electric vehicle

HWFET	Highway Federal Emissions Test
ICE	internal combustion engine
IVM	initial vehicle movement
Li-ion	lithium ion
MY	model year
NiMH	nickel metal hydride
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
PHEV25	PHEV with 25 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
PHEV40	PHEV with 40 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
PHEV50	PHEV with 50 miles of all-electric range (end-of-life) on Combined Driving Cycle (adjusted)
P/W	power-to-weight [ratio]
R&D	research and development
SAE	Society of Automotive Engineers
SI	spark ignition
SOC	State of Charge
SUV	Sport Utility Vehicle
UDDS	Urban Dynamometer Driving Schedule
USD	U.S. Dollars
U.S.DRIVE	United States Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability [Program]
VCR	variable compression ratio
VTO	Vehicle Technologies Office
VTS	vehicle technical specifications
VVT	variable valve timing

UNITS OF MEASURE

A	ampere(s)
Ah	ampere-hour(s)
bbl	barrel(s)

°C	degree(s) Celsius
°F	degree(s) Fahrenheit
gal	gallon(s)
h	hour(s)
kg	kilogram(s)
km	kilometer(s)
kW	kilowatt(s)
L	liter(s)
lb	pound(s)
m	meter(s)
m^2	square meter(s)
mi	mile(s)
mpg	mile(s) per gallon mph
mph	mile(s) per hour
sec	second(s)
V	volt(s)
Wh	watt hour(s)

PREFACE

This report refers to a continuous improvement study on Benefits and Scenario Analysis (BaSce) from the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) and corresponds to the fourth revision of the study. Past reports include:

1. "Assessment of Vehicle Sizing, Energy Consumption and Cost through Large-Scale Simulation of Advanced Vehicle Technologies" (Moawad et al. 2016, March)

2. "Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045" (Moawad 2014, April)

3. "Light-Duty Vehicle Fuel Consumption Displacement Potential up to 2045" (Moawad 2011, July)

Links to these reports are on the Argonne Autonomie webpage at http://www.autonomie.net/publications/fuel_economy_ report.html. The webpage also contains a link to the assumptions ("Main Assumptions") and results ("Results per component" and "Results per vehicle") for each of the revisions.

With each revision of the study, changes were made to the assumptions, control strategies at the vehicle level, methodologies, and powertrain selections.

ABSTRACT

This report reviews the results of the research developed through the support of DOE VTO. It provides an assessment of the fuel and light-duty vehicle technologies that are most likely to be published, developed, and eventually commercialized during the next 30 years (up to 2050). Because of the rapid evolution of component technologies, this study is updated at specific time intervals to continuously update the results based on the latest state-of-the-art technologies.

While it is not possible to simulate all the possible vehicle powertrain combinations, more than 5,000 representative vehicles are simulated in the study to take the following into account:

- Multiple powertrain configurations (i.e., conventional, power-split, extended-range electric vehicle, battery electric drive, and fuel-cell vehicles),

- Vehicle classes (i.e., compact car, midsize car, small sport utility vehicle [SUV], midsize SUV, and pickup trucks), and

- Fuels (i.e., gasoline, diesel, and battery electricity).

These various technologies are assessed for six different timeframes: laboratory (lab) years 2010 (reference), 2015, 2020, 2025, 2030, and 2045. A delay of five years is assumed between lab year and model year (year technology is introduced into production). Finally, uncertainties are included for both technology performance and cost aspects by considering three cases:

- Low case – aligned with original equipment manufacturer (OEM) improvements based on regulations,

- Medium case, and

- High case– aligned with aggressive technology advancements based on R&D targets developed through support by VTO.

Low technology progress represents a very small uncertainty in achieving the target, i.e., the manufacturers would achieve this target without the advancement of DOE VTO programs. The high technology progress represents a very high uncertainty in achieving the target by the manufacturers as they correspond to DOE VTO targets for the corresponding technology and lab year. The medium case corresponds to the average of the two extreme uncertainty levels.

This report provides an assessment of the fuel displacement and cost-reduction potentials of advanced technologies up to the year 2045, including the different uncertainty levels.

EXECUTIVE SUMMARY

The U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO), along with Fuel Cell Technologies Office (FCTO) supports new technologies to increase energy security in the transportation sector at a critical time for global petroleum supply, demand, and pricing, with goals to improve energy efficiency, reduce energy use, and save money of the consumers.

The U.S. transportation sector used about 14 million barrels of oil equivalent per day in 2015 (Figure ES.1).

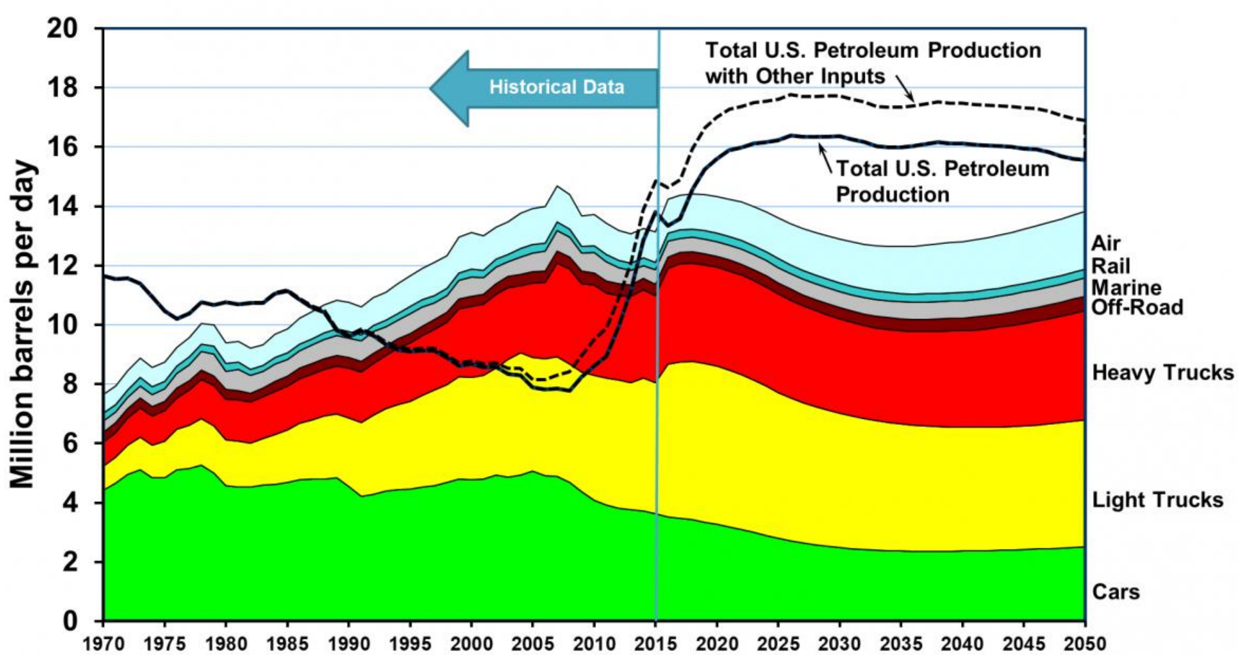

FIGURE ES.1 U.S. petroleum production and transportation consumption 1970–2050 (Source: Energy.gov 2017a)

VTO collaborates with industry to identify priority areas of research needed to develop advanced vehicle technologies to reduce petroleum use, and to reduce emissions. VTO works on numerous technologies, including the following:

- Development of hybrid electric vehicles (HEVs) and plug-in HEVs (PHEVs), through advanced batteries, electric machines, and power electronics
- Reduction of vehicle weight (lightweighting)
- Improvement of combustion technologies and optimization of fuel systems

The objective of the present study is to evaluate the benefits of DOE VTO for a wide range of vehicle applications, powertrain configurations, and component technologies for different timeframes, and to quantify the potential future impacts up to 2045, as well as the cost evolution. More than 5,000 light-duty vehicles were simulated with Autonomie, Argonne National Laboratory's vehicle simulation tool.

To address performance and cost uncertainties, three cases were considered: low, average, and high uncertainty. The assumptions were developed through discussions with experts from industry, universities, and the national laboratories.

A vehicle is defined through several hundred assumptions. Some of the assumptions are highlighted below:

- The difference in peak efficiency between gasoline and diesel engines is expected to narrow in the future because of the combination of advanced gasoline engine technologies and the impact of evermore stringent after treatment requirements for diesel.

- Coupling ultra-capacitors with batteries was not considered, owing to higher cost and expected increase in lithium ion battery life and cold-start performance in the short term.

- Automated manual transmissions were not included in the study.

ES.1 VEHICLE POWERTRAIN SIZING

Advances in material substitution will play a significant role in reducing overall vehicle weight, and consequently, in reducing component power and energy requirements.

- Vehicle weight reductions (lightweighting) has greater influence on electric drive vehicles (EDVs) than on their conventional counterparts owing to the impact of the battery weight on EDVs.

The different PHEVs show a linear relationship between usable battery energy and vehicle mass, with the slope increasing with the AER.

ES.2 VEHICLE FUEL EFFICIENCY

Overall, the combination of technology improvements leads to significant fuel-consumption reduction across vehicle applications resulting in energy efficiency improvements in the transportation sector.

ES.2.1 Evolution of Fuel Consumption Compared with Reference 2010 Gasoline Conventional Vehicles

Table ES.1 summarizes the unadjusted fuel consumption reduction by 2045 on the combined driving cycle for each powertrain configuration and fuel compared with the reference 2010 gasoline conventional vehicle.

TABLE ES.1 Percentage gasoline-gallon equivalent fuel consumption reduction of each powertrain by 2045, compared with reference 2010 gasoline conventional powertrain

Fuel/ Powertrain	Conventional	HEV	PHEV25	PHEV40	PHEV50
Gasoline	23–49	50–73	78–89	84–92	87–94
Diesel	23–51	43–68	73–85	82–91	86–92
Fuel Cell		68–81	86–92	91–95	93–96

The results demonstrate significant improvements over time across all powertrain configurations and fuel types. When considering the low/high uncertainty cases across all engines, conventional vehicles can achieve a 23% to 51% fuel consumption improvement; power-split HEVs can achieve a 43% to 81% improvement; 73% to 92% for PHEV25; 82% to 95% for PHEV40; and 86% to 96% for PHEV50.

ES.2.2 Evolution of Specific Powertrains

Table ES.2 shows the 2045 unadjusted fuel-consumption reduction on the combined driving cycle for each powertrain configuration and fuel, compared with each configuration's current status in 2010 (e.g., the diesel HEV in 2045 is compared with the reference diesel HEV in 2010).

TABLE ES.2 Percentage fuel-consumption reduction across powertrains by 2045 compared with the respective current status in 2010 (values reflect the uncertainty range)

Fuel/ Powertrain	Conventional	Power-split HEV	PHEV25	PHEV40	PHEV50
Gasoline	23–49	28–59	33–63	27–63	29–62
Diesel	18–47	21–55	31–60	28–65	26–58
Fuel Cell		23–51	27–59	26–61	28–67

The results demonstrate that the maximum improvement expected for each powertrain technology compared with the current status ranges from 18% to 67%. The range depends on fuels (i.e., diesel vehicles show less improvement than gasoline vehicles) and powertrain (i.e., conventional engines have a lower maximum improvement than PHEV50 engines).

ES.3 MANUFACTURING COST

The combined technology improvements result in cost reductions across some vehicle components that affect manufacturing costs. Owing to these cost reductions, advanced vehicle technologies are expected to have a significant market penetration over the next decade.

ES.3.1 Evolution of Costs for Specific Powertrains

Table ES.3 compares the percent change in manufacturing costs between 2010 and 2045 for each powertrain configuration to the reference 2010 value.

TABLE ES.3 Percent change in manufacturing cost for each powertrain by 2045 compared with its respective (same powertrain) 2010 manufacturing cost for midsize cars

Fuel/ Powertrain	Conven-tional	Power-split HEV	PHEV25	PHEV40	PHEV50	BEV100	BEV200	BEV300
Gasoline	+2 – +18	-11 – +36	-26 – -2	-33 – -9	-18 – -38			
Diesel	-1 – +13	-18 – +26	-30 – -6	-36 – -13	-40 – -20			
Fuel Cell		-13 – +61	-26 – +16	-30 – +3	-34 – -6			
BEV						-25 – +50	-35 – +64	-42 – +78

The manufacturing costs for gasoline and diesel conventional vehicles increase over time owing to the effects across several factors, such as lightweighting and advanced vehicle component technologies (direct injection, etc.). In contrast, the greatest reductions are noticed for the vehicles with high-energy batteries and fuel-cell systems.

Due to the expected improvements in batteries, manufacturing cost reductions have a greater effect on batteries with higher energies. As a result, PHEV50s demonstrate a larger cost reduction than PHEV25s across all fuels. PHEV50s with gasoline engines show cost reductions ranging between 18% and 38% from 2010 to 2045, while PHEV25s show a cost reduction ranging from only 2% to 26%.

The fuel-cell vehicle manufacturing costs decrease significantly over time. From 2010 to 2045, the manufacturing costs for fuel-cell HEVs decrease by about 13%; for fuel-cell PHEV25s, by 26%; for PHEV40s, by 30%; and for fuel-cell PHEV50s, by about 6% to 36%. Also, the results show that for some combinations the manufacturing price may increase by 2045, owing mainly to the glider cost increase over time, whereas no other component benefits from cost reduction over time. However, the hybrid vehicles tend to get cheaper owing to advances in battery technology that result in cost reductions over time.

ES.3.2 Powertrain Comparison

The manufacturing cost differences between powertrain options tend to decrease over time. In 2010 lab year, for midsize vehicle class, the gasoline power-split HEV is about 28% more expensive than the conventional vehicle, PHEV25 is about 64% more expensive, PHEV40 is about 95% more expensive, and PHEV50 is about 110% more expensive. By 2045, these differences are 11% for HEV, 18% for PHEV25, 29% for PHEV40, and 29% for PHEV50.

ES.3.3 Fuel-Comparison Evolution

A comparison of gasoline vs. diesel engines shows the following:

- Conventional diesel vehicle manufacturing costs remain between 8% and 11% more expensive than the gasoline vehicles by 2045.

- Diesel-powered HEVs are about 4% to 6% more expensive to manufacture when compared to gasoline HEVs by 2045.

- Diesel-powered PHEV25s are about 6% more expensive to manufacture when compared to gasoline PHEV25s by 2045.

- Diesel-powered PHEV40s are about 5% more expensive to manufacture when compared to gasoline PHEV40s by 2045.

- Diesel-powered PHEV50s are about 5% more expensive to manufacture when compared to gasoline PHEV50s by 2045.

ES.4 CONCLUSION

Technology improvements lead to significant energy consumption and cost reductions across light-duty vehicle applications. Because of the uncertainty of the evolution of the technologies considered, different areas of development reflect varying potential improvements.

Because of the expected improvements, advanced technologies are anticipated to impact in vehicle energy consumption over the next decade. In the short term, both engine HEVs and PHEVs allow a significant fuel displacement with additional costs. For the long term, fuel-cell vehicles and battery electric vehicles demonstrate very high fuel displacement potentials.

1 INTRODUCTION

1.1 BACKGROUND

In 2016, petroleum accounted for about 35% of the world's energy use. Reports indicate that the United States is the world's highest oil-consumer with a consumption rate of about 20 million barrels per day (Transportation Energy Data Book, 2017a). With only 4.5% of the world's population, the United States consumes almost a quarter of the world's oil.

According to the Energy Information Administration (EIA), the transportation sector is almost entirely dependent on oil as its primary energy source (EIA 2017). The number of vehicles in the United States is growing significantly faster compared to the U.S. population itself (Transportation Energy Data Book, 2017b).

It has also been reported that an average U.S. household spends about 16% of their household income in transportation. About 48% of that is spent on vehicle purchases and maintenance while 21% in spent on gasoline and motor oil expenses (Transportation Energy Data Book, 2017c). During the past 30 years, major oil price shocks have disrupted the world energy markets five times, and most of the shocks were followed by a period of recession in the United States economy.

Such a strong dependence on oil has important consequences to the nation and its economy. To address this issue, the U.S. government, and in particular the U.S. Department of Energy (DOE) has developed various projects to find alternative and efficient energy solutions for the transportation domain.

The U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) has been supporting the development of more energy-efficient highway transportation technologies that will enable Americans to save money and energy. The long-term aim is to develop "leapfrog" technologies that will provide Americans with greater freedom of mobility and energy security, while lowering costs and reducing environmental effects. DOE's VTO examines pre-competitive, high-risk research needed to develop:

- Component and infrastructure technologies necessary to enable a full range of affordable cars and light-duty trucks

- Fueling infrastructure to reduce the dependency of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice

As part of the program, numerous technologies are addressed, including engines, energy storage systems, fuel-cell systems, hydrogen tank storage, electric machines, and materials. The 1993 Government Performance and Results Act (GPRA) holds federal agencies accountable for using resources wisely and achieving program results. GPRA requires agencies to develop plans for what they intend to accomplish, to measure how well they are doing, to make appropriate decisions on the basis of the information that they have conquered, and to communicate information about their performance to the U.S. Congress and to the public. The present study evaluates the benefits of the light-duty vehicle research conducted at DOE from the perspective of fuel-efficiency and cost to support GPRA activities.

Because of the large number of component and powertrain technologies considered as well as the accuracy and precision of modeling, the benefits are simulated using Autonomie. Argonne National Laboratory developed Autonomie to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process, from vehicle components modeling to control. Autonomie is a forward-looking mathematical model, developed using Mathworks tools that offers the ability to quickly compare a very large number of vehicle powertrain configurations and component technologies from the perspective of performance, fuel-efficiency, and cost.

2 METHODOLOGY

2.1 AUTONOMIE OVERVIEW

Many of today's automotive control system simulation tools are suitable for modeling, but provide rather limited support for model building and management. Autonomie (Argonne 2017) is a MATLAB-based software environment and framework for automotive control system design, simulation, and analysis. The tool is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (e.g., calibration, validation). Developed by Argonne National Laboratory (Argonne) in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineering throughout the development process from modeling to control. Autonomie was built to accomplish the following:

- Support proper methods, from model-in-the-loop, software-in-the-loop, and hardware- in-the-loop to rapid-control prototyping;

- Integrate math-based engineering activities through all stages of development, from feasibility studies to production release;

- Promote reuse and exchange of models industry-wide through its modeling architecture and framework;

- Support user customization of the entire software package, including system architecture, processes, and post-processing;

- Mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding are critical;

- Link with commercial off-the-shelf software applications, including GT-Power, AMESim, and CarSim, for detailed, physically-based models;

- Provide configuration and database management; and

By building models automatically, Autonomie allows the quick simulation of a very large number of component technologies and powertrain configurations. Autonomie can do the following:

- Simulate subsystems, systems, or entire vehicles;

- Predict and analyze fuel efficiency and cost;

- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;

- Support system hardware and software requirements;

- Link to optimization algorithms; and

- Supply libraries of models for propulsion architectures of conventional powertrains as well as EDVs.

Autonomie is used to evaluate the energy consumption and cost of advanced powertrain technologies. It has been validated for several powertrain configurations and vehicle classes using Argonne's Advanced Powertrain Research Facility (APRF) vehicle test data (Kim et al. 2013; Kim et al. 2012; Kim et al. 2009; Rousseau et al. 2006; Cao 2007; Rousseau 2000; Pasquier et al. 2001).

Autonomie is the primary vehicle simulation tool selected by DOE to support its U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (DRIVE) Program and Vehicle Technologies Office (VTO). Autonomie has been used for numerous studies to provide the U.S. government with guidance for future research. More than 175 companies and research entities, including major automotive companies and suppliers, use Autonomie to support their advanced vehicle development programs.

2.2 ASSUMPTIONS DEVELOPMENTS

The assumptions for the study (i.e., component assumptions, control strategies, vehicle technical specifications [VTS], sizing algorithms) are developed and regularly updated through numerous discussions with component and system experts.

An assumption is defined after taking into account several inputs from the different experts related to an area of expertise for each uncertainty and timeframe considered. The assumptions are detailed in Chapter 3.

2.3 STUDY PROCEDURE

The procedure to conduct the study and estimate the energy consumption of various advanced vehicle powertrains can be divided into the following steps:

- **Architecture definition:** The vehicle architecture is built using the different components available in the main database. In this study, each individual component is associated with different technology progress/cost uncertainties (low, average, and high).

- **Component sizing:** State-of-the-art sizing algorithms are used to size the vehicle components in order to differentiate the broad vehicle models choices. Once the sizing is complete, all the component features are known and it is possible to estimate the retail price of the vehicle. The sizing algorithms are specific for each configuration and are discussed in detail later.

- **Simulation runs:** The vehicle energy consumption is calculated by simulating the different standard U.S. test procedures.

2.4 TIMEFRAMES AND UNCERTAINTIES

Each vehicle is designed from the ground up, based on each component assumptions to evaluate the fuel-efficiency benefits. The energy consumption is then simulated using the Urban Dynamometer Driving Schedule (UDDS) and Highway Federal Emissions Test (HWFET). The vehicle costs are calculated from individual component characteristics (e.g., power, energy, weight). The process is illustrated in Figure 2.1 below.

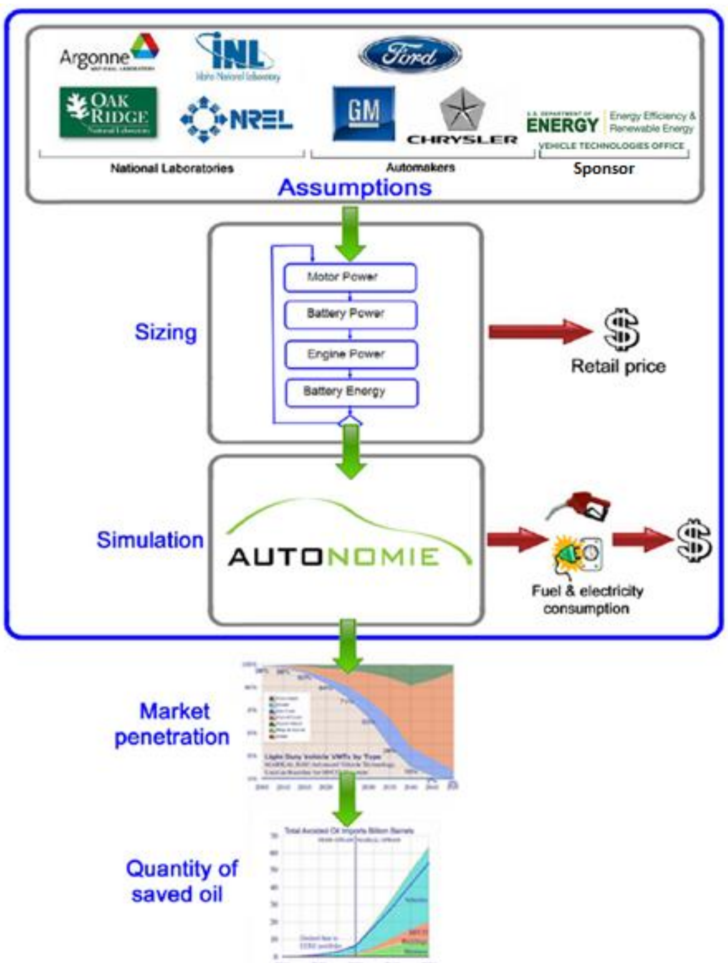

FIGURE 2.1 Process to evaluate fuel efficiency of advanced vehicle technologies

To enable the detailed assessment of the benefits of future technologies, several options are considered:

- **Five vehicle classes:** Compact, midsize car, small SUV, midsize SUV, and pickup truck.

- **Six timeframes:** 2010 (reference), 2015, 2020, 2025, 2030, and 2045. All years considered are "lab years" with a 5-year delay to production year.
- **Seven powertrain configurations:** Conventional, HEV, PHEV, split HEV, split PHEV, Fuel Cell (FC) HEV, and battery electric vehicle (BEV).

- **Three technology progress uncertainty levels:** Low, medium, and high cases. These correspond to low uncertainty (aligned with original equipment manufacturer [OEM] improvements based on regulations), average uncertainty, and high uncertainty (aligned with aggressive technology advancement based on DOE VTO programs). Low technology progress represents a very small uncertainty in achieving the target, i.e., the manufacturers would achieve this target without the advancement of DOE VTO programs. The high technology progress represents a very high uncertainty in achieving the target by the manufacturers as they correspond to DOE VTO targets for the corresponding technology and lab year. The medium case corresponds to the average of the two extreme uncertainty levels.

As a result, more than 10,000 vehicles are defined and simulated in Autonomie. Figure 2.2 displays the simulation options.

When dealing with uncertainties, numerous methodologies are available. In previous studies, Argonne has compared Monte Carlo simulation with a triangular distribution analysis (Faron et al. 2009). By allowing the introduction of uncertainty into our algorithm inputs, the Monte Carlo method increases the amount of useful information to describe the possible behaviors of a vehicle. The major improvement concerns the introduction of the risk notion associated with each result. Rather than providing a single forecast value, Monte Carlo simulation provides the uncertainty of occurrences associated with every possible output value. As a result, forecasts are described more fully and accurately and confidence intervals can be derived for each output.

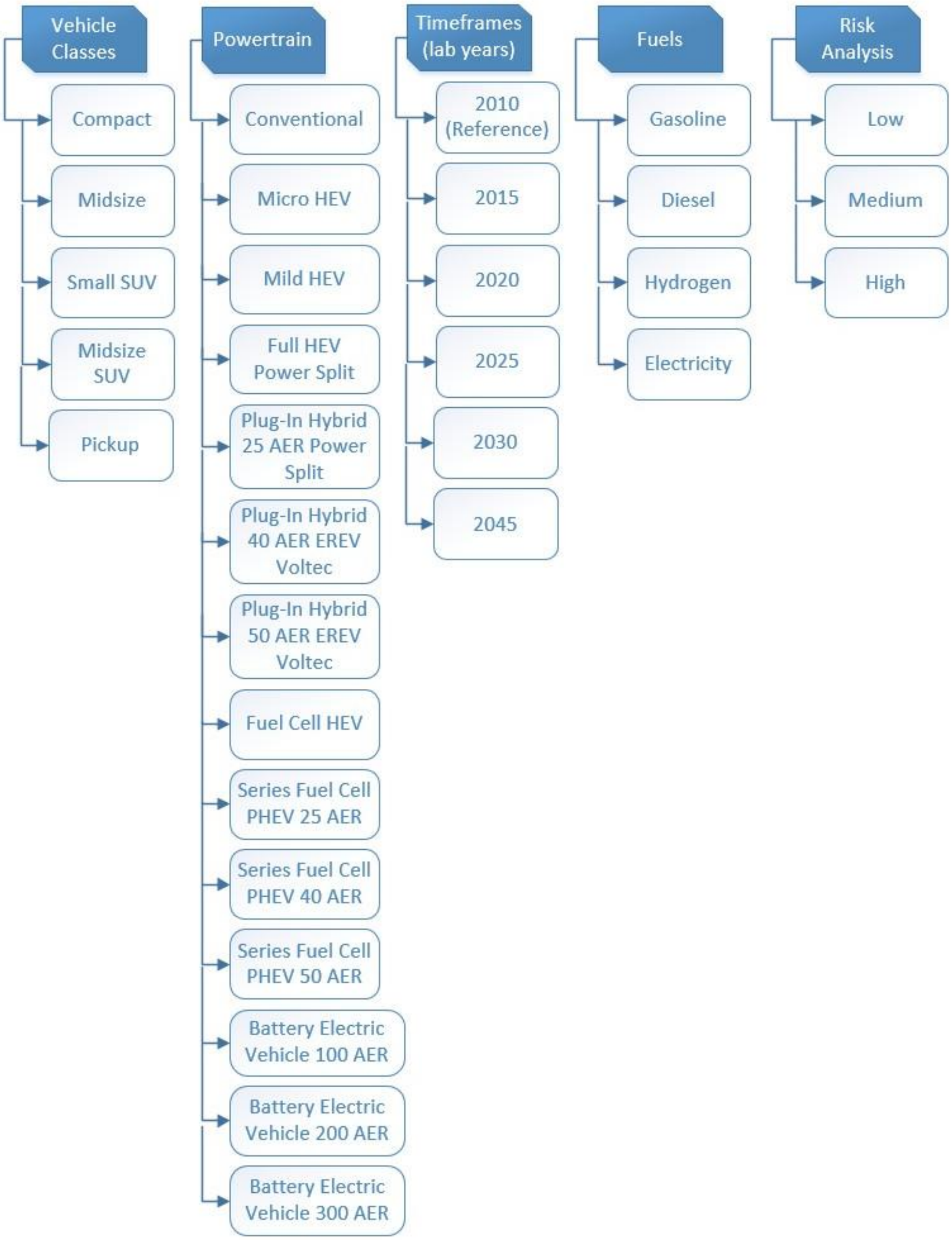

FIGURE 2.2 Vehicle classes, timeframes, configurations, fuels, and uncertainty levels

2.5 HIGH PERFORMANCE COMPUTING UTILIZATION

Simulating the vast number of technology combinations possible using conventional computing resources is not feasible in the study. Months or even several years would be needed to run all the simulations on a single computer. Therefore, the study uses high performance computing capabilities, and with distributed computing resources, the total simulation time is greatly reduced. Figure 2.3 illustrates the detailed process for distributed computing.

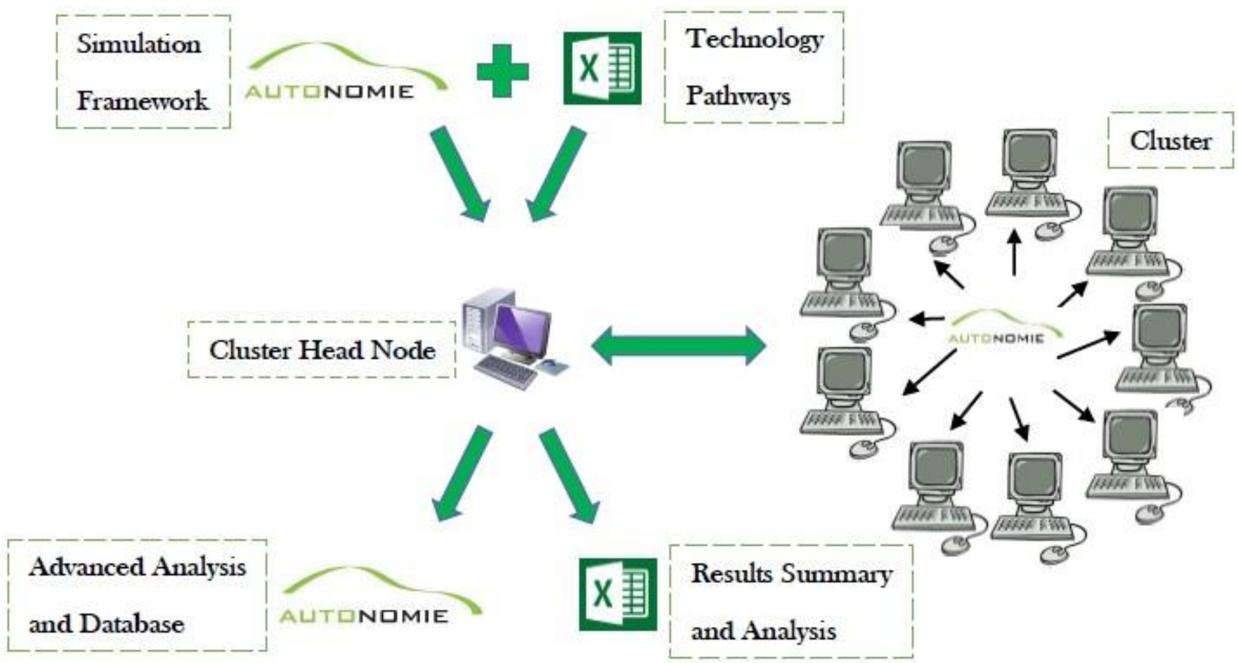

FIGURE 2.3 Distributed computing process

3 COMPONENT ASSUMPTIONS

Individual vehicle component assumptions have been determined in collaboration with experts from DOE, other national laboratories, industry, and academia. Each vehicle simulation utilizes a number of component assumptions. Figures 3.1 and 3.2 define the list of parameters explored for the individual components and vehicles, respectively.

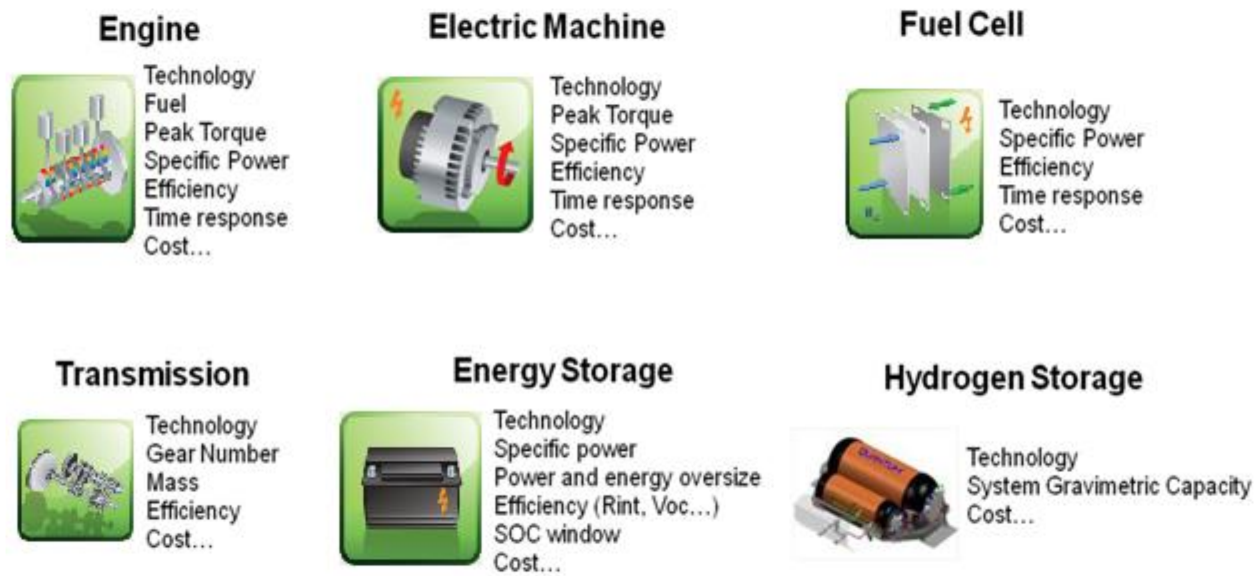

FIGURE 3.1 Main vehicle component parameters

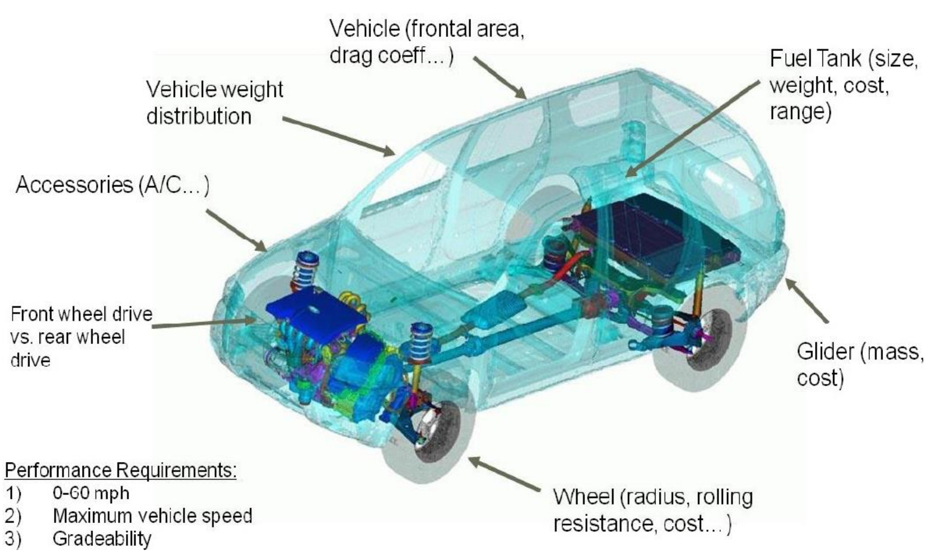

FIGURE 3.2 Vehicle parameters

3.1 ENGINE

3.1.1 Reference Engines and Projections

Latest designs of internal combustion engines (ICEs) with cutting-edge technologies are selected as the baseline for the different fuel types considered: gasoline (spark-ignition [SI]) and diesel (compression-ignition [CI]). The engines used for HEVs and PHEVs are based on Atkinson cycles generated from test data collected of a 2010 Toyota Prius at Argonne's dynamometer testing facility. Table 3.1 below details the engines selected as a baseline for the study.

TABLE 3.1 Baseline engine definitions used in the present study

Fuel	Source	Displacement (L)	Peak Power (kW)
SI (conventional)	Car manufacturer	2.4	107.9
CI (conventional)	Car manufacturer	1.9	140.7
SI (HEV)	Argonne	1.497	73
CI (HEV)	Argonne	1.9	140.7

A wide range of technologies has been designed to increase engine efficiencies, including:

- Low-friction lubricants
- Reduced engine friction losses
- Cylinder deactivation
- Variable Valve Timing (VVT) and Variable Valve Lift (VVL)
- Turbocharging and downsizing
- Variable compression ratio (VCR)
- Stoichiometric and lean-burn gasoline direct injection

The peak efficiencies have been decided for each fuel type and timeframe after discussions with experts and literature review. Figure 3.3 below illustrates the engine peak efficiencies for a conventional powertrain across the different lab years. The low, medium, and high labels correspond to the different technology performance cases.

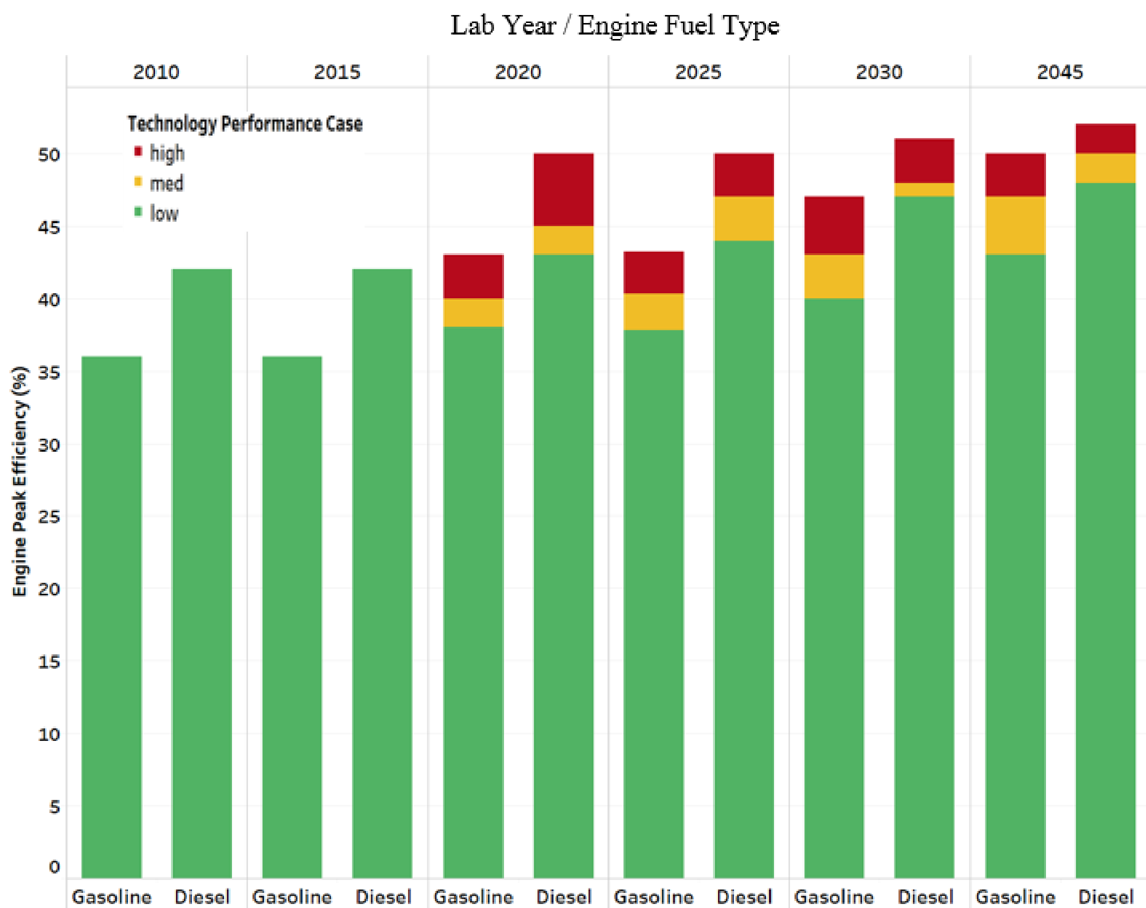

FIGURE 3.3 Engine peak efficiency assumptions

3.1.2 Determination of Number of Cylinders

To calculate the engine cost, the number of cylinders are defined at a given power level. Figure 3.4 shows the relationship between the number of cylinders in a gasoline engine and the engine peak power for vehicles sold in 2015 in the U.S. market (Moawad et al. 2015).

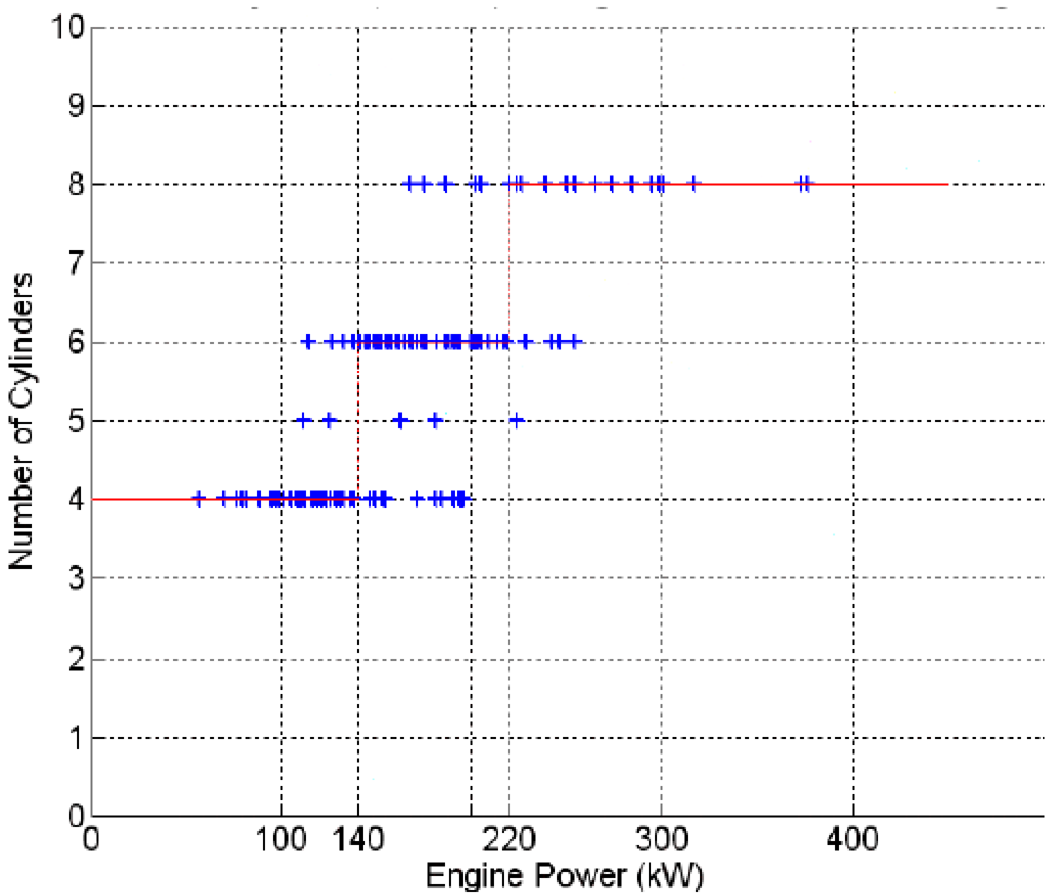

FIGURE 3.4 Number of cylinders vs. engine power for gasoline engines for vehicles sold in 2015 in the U.S. market (Moawad et al. 2015)

It can be concluded from the graph that 4-cylinder engines are typically used up to a power level of 140 kW, 6-cylinder engines are used between 140 and 220 kW, and 8-cylinder engines are used for engine powers above 220 kW.

A similar approach is taken to determine the number of cylinders for diesel engines based on engine power. Because of the limited number of diesel engines available for survey, a clear distinction between number of cylinders and engine power cannot be made; however, the power threshold for gasoline engines appears to hold for diesel engines. Figure 3.5 shows the relationship for diesel engines.

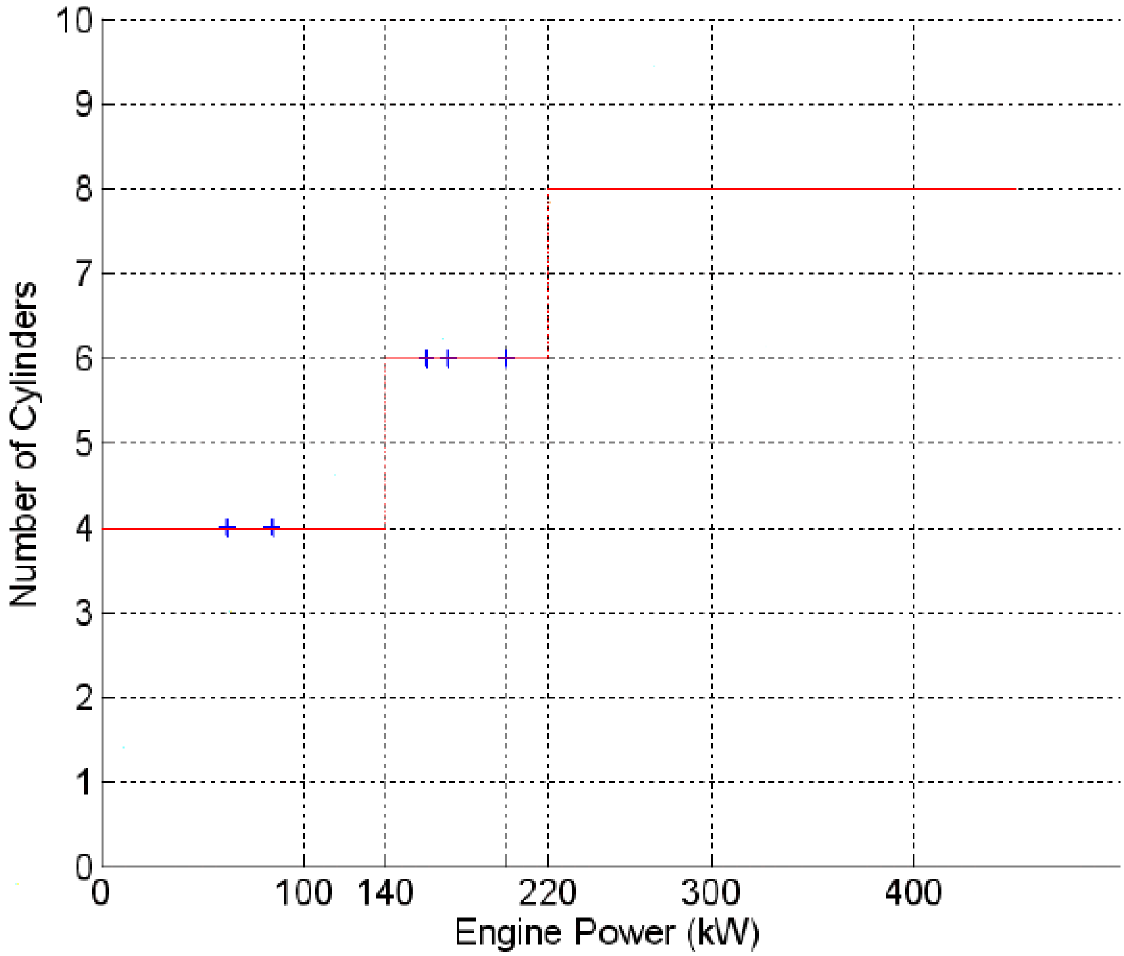

FIGURE 3.5 Number of cylinders vs. engine power for diesel engines for vehicles sold in 2015 in the U.S. market (Moawad et al. 2015)

3.2 FUEL-CELL SYSTEM

Figure 3.6 illustrates the power density of fuel-cell systems and shows that, between the reference case of lab year 2010 and lab year 2045, the power density increases from 650 W/kg for the low scenario to up to 870 W/kg for the high scenario. Note that in year 2020, the power density assumptions for all three cases are the same. The low, medium, and high labels correspond to the three different technology performance cases considered in the study.

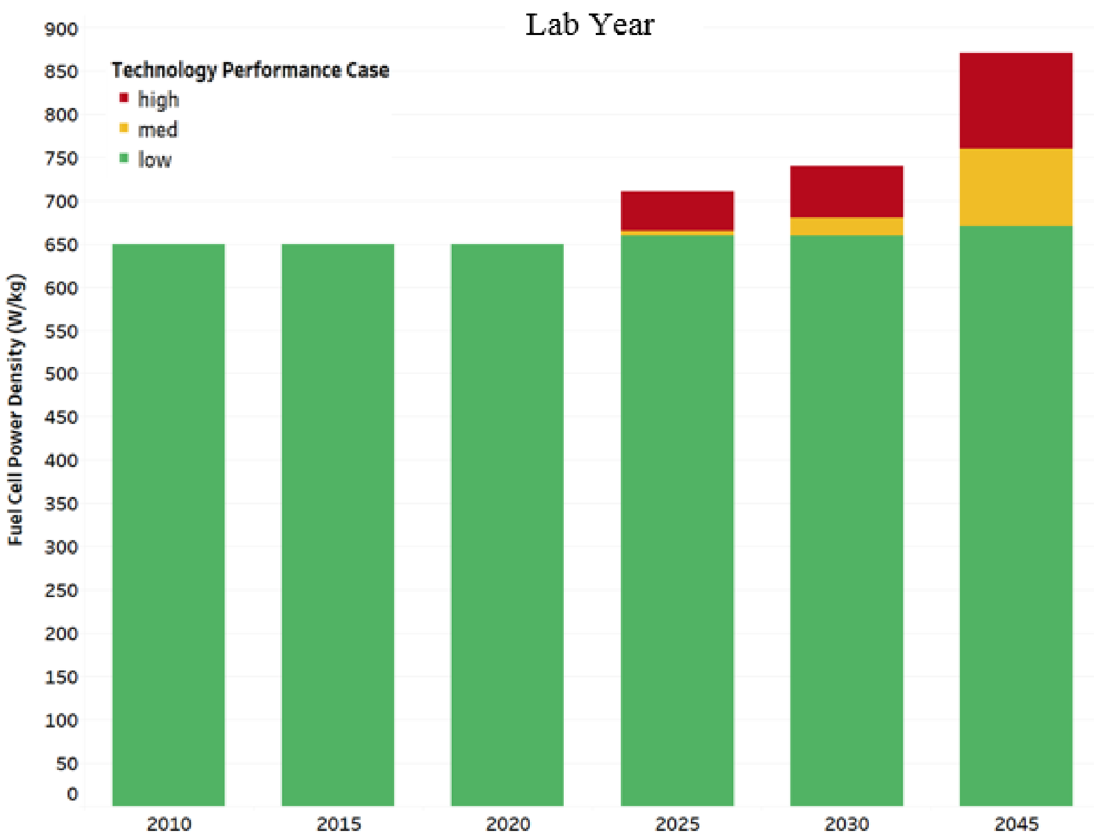

FIGURE 3.6 Fuel cell power density assumptions

The fuel cell system simulated has been sized to a range of 320 miles on the adjusted combined cycle. In addition, 100% of the H_2 present in the tank is referred to as usable. Figure 3.7 illustrates the assumptions of fuel-cell system peak efficiencies. The low, medium, and high labels correspond to the three different technology performance cases considered in the study.

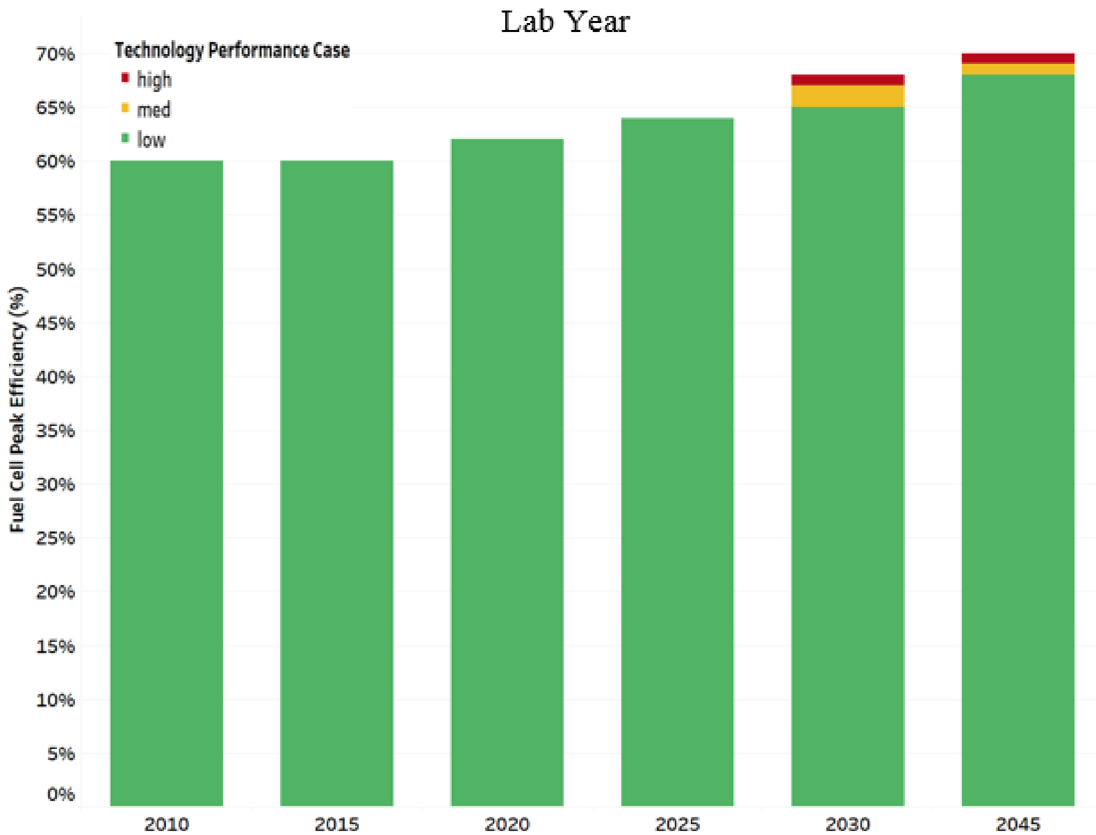

FIGURE 3.7 Fuel cell peak efficiency assumptions

The fuel-cell peak efficiency is assumed to be at 60% for the reference case (lab year 2010), which increases to 70% for the lab year 2045 case.

3.3 ELECTRIC MACHINE

Two different electric machines are used as references in this study:

- Power-split vehicles use a permanent magnet electric machine (similar to the Toyota Camry)
- Series configuration (fuel cells) and EVs use an induction primary electric machine

The reference electric machine data are provided by car manufacturers, suppliers, and Oak Ridge National Laboratory. (ORNL, 2008)

The power electronics specific power significantly increases between 2010 (reference) and 2045 lab years. See Table 3.2.

TABLE 3.2 Electric machine assumptions

	2010	2015	2020			2025			2030			2045		
	Ref	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
High Voltage System Specific Power (W/kg)	1125	1125	1350	1395	1440	1500	1550	1600	1700	1750	1800	1900	1950	2000
High Voltage System Peak Efficiency (%)	91%	92%	92%	94%	96%	93%	95%	96%	94%	95%	96%	95%	96%	97%

It is assumed that the peak efficiency of the electric machines will increase from 90% to 97% from 2010 lab year to 2045 lab year.

3.4 ENERGY STORAGE SYSTEM

The battery performance data used in the study are provided by Argonne, Idaho National Laboratory, and major battery suppliers (Jim, 2014). A scaling algorithm developed by Argonne is used for the high-energy cases (Nelson et al. 2007).

Based on the performance data provided by Argonne, the HEV, PHEV and BEV applications use a lithium-ion (Li-ion) battery. Table 3.3 below provides a summary of the battery characteristics.

TABLE 3.3 Battery assumptions

	2010	2015	2020			2025			2030			2045		
Parameter (%)	Ref	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
SOC Max– PHEVs	95	95	95	95	95	95	95	95	95	95	95	95	95	95
SOC Min–PHEVs	25	25	25	25	20	20	15	10	20	15	10	15	10	5
SOC Max–HEVs	70	70	70	75	80	80	80	80	80	85	90	85	90	95
SOC Min–HEVs	50	50	50	45	40	40	30	20	20	15	10	15	10	5
SOC Max– BEVs	95	95	95	95	95	95	95	95	95	99	99	99	99	99
SOC Min– BEVs	5	5	5	5	5	5	5	5	5	5	5	5	5	5

3.5 DRIVELINE

During the course of this study, various transmission technologies are considered:

- Automatic transmission: To enable the engine to operate closer to the peak efficiency, additional gears have been incorporated for the later years. While they are now limited to high-end vehicles, high gear-count (i.e., up to eight gears) are expected to be used in a larger number of vehicles in the near future.

- Dual-clutch transmission (DCT): Every car manufacturer is working on developing this technology, and some already have DCT models in production. DCTs combine the advantages of automatic transmissions (better drive quality—no torque interruption) and manual transmissions (higher efficiency—no torque converter).

Conventional vehicles are simulated with an automatic transmission, since that option best represents the average car available in the U.S.

Power-split HEVs and PHEVs both have a planetary gear set with 78 ring teeth and 30 sun teeth. Finally, the fuel-cell vehicles and EVs use a two-speed manual transmission to increase the powertrain efficiency as well as allow them to achieve a maximum vehicle speed of at least 100 mph.

Figure 3.8 illustrates the peak efficiencies of the different driveline technologies considered for the study, across the different timeframes.

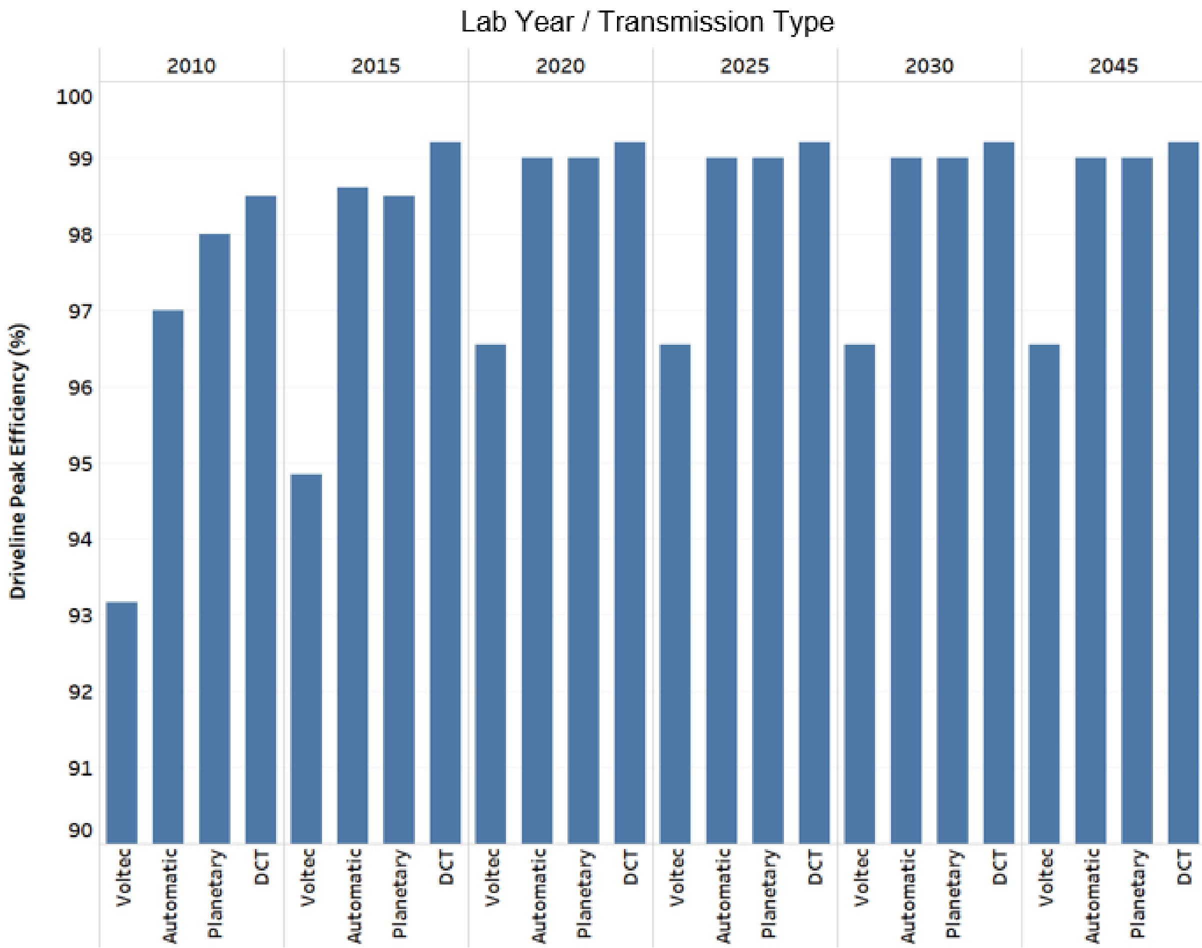

FIGURE 3.8 Driveline peak efficiency

3.6 BODY AND VEHICLE

3.6.1 Technology Overview

Vehicle weight is considered one of the main factors when considering energy consumption. Lightweighting (i.e., lowering the vehicle weight) reduces the normal force required to follow the vehicle speed trace. This results in component downsizing, which has a direct effect on fuel consumption due to smaller components. However, different powertrains provide different effects on energy consumption from lightweighting.

Methods of lightweighting include material substitution (high-strength low-alloy steel, aluminum, magnesium, etc.), improved packaging, and unibody construction. (Moawad et al. 2015)

Energy consumption can also be improved by reducing rolling resistance, frontal area, and drag coefficient, providing the potential to reduce the force required at the wheels. However, this study assumes that the frontal area would increase in future years because American consumers have demanded vehicles with greater passenger and cargo volumes as observed through market penetration studies.

Table 3.4 illustrates the main characteristics used as a reference for lab year 2010.

TABLE 3.4 Reference characteristics across vehicle classes

Vehicle Class	Glider Mass (kg)	Frontal Area (m^2)	Tire	Wheel Radius (m)	Cd
Compact	943	2.331	P195/65/R15	0.325	0.323
Midsize	1105	2.372	P195/65/R15	0.325	0.311
Small SUV	1213	2.841	P225/75/R15	0.375	0.366
Midsize SUV	1260	2.9376	P235/70/R16	0.35	0.366
Pickup	1500	3.2742	P255/65/R17	0.325	0.44

3.6.2 Lightweighting

Figure 3.9 illustrates the effect of lightweighting on the glider mass across the different vehicle classes/lab years. The low, medium, and high cases illustrate the different technology performance cases. It is observed that the glider mass is reduced by up to 32% in the 2045 high case. The assumption of reduction can be explained by the use of better materials and technologies in the future, such as aluminum unibody structures.

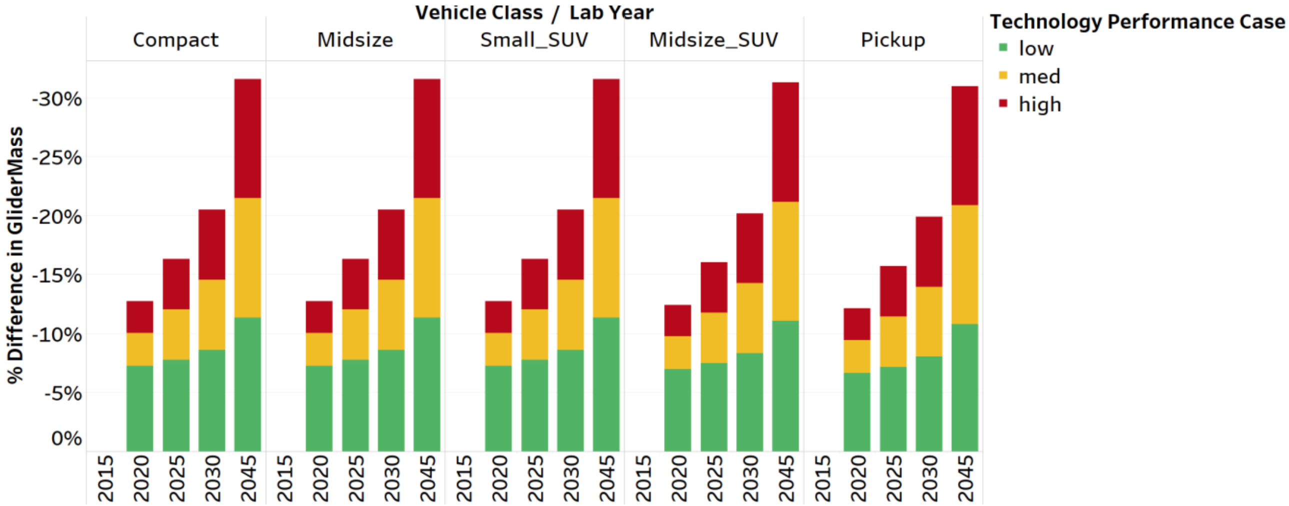

FIGURE 3.9 Lightweighting across vehicle classes and lab years

3.6.3 Drag Coefficient and Rolling Resistance

It is also assumed that the drag coefficient and rolling resistance values of the different vehicle classes reduce in the future, which leads to an improvement in the overall opposing force to the vehicle and hence results in an improvement in energy consumption.

Table 3.5 below summarizes the rolling resistance assumptions for the different vehicle classes.

TABLE 3.5 Rolling resistance assumptions

	2010	2015	2020			2025			2030			2045		
Parameter	Low	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Compact	0.008	0.008	0.008	0.0075	0.007	0.008	0.0075	0.007	0.0075	0.007	0.006	0.007	0.0066	0.006
Midsize	0.008	0.008	0.008	0.0075	0.007	0.008	0.0075	0.007	0.0075	0.007	0.006	0.007	0.0066	0.006
Small SUV	0.0084	0.008	0.008	0.0075	0.007	0.008	0.0075	0.007	0.008	0.007	0.006	0.0078	0.0066	0.006
Midsize SUV	0.0082	0.0082	0.008	0.0078	0.0075	0.008	0.0078	0.0075	0.008	0.0078	0.007	0.0078	0.0074	0.007
Pickup	0.0088	0.0088	0.0084	0.0082	0.008	0.0084	0.0082	0.008	0.0082	0.008	0.0078	0.008	0.0078	0.0076

It is assumed that the rolling resistance of the different classifications of vehicles reduces by about 13% - 25% by the year 2045 compared to the reference year in 2010.

Table 3.6 below summarizes the drag coefficient assumptions for the different vehicle classes.

TABLE 3.6 Drag coefficient assumptions

	2010	2015	2020			2025			2030			2045		
Parameter	Low	Low	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
Compact	0.323	0.323	0.323	0.306	0.287	0.323	0.306	0.287	0.29	0.27	0.25	0.28	0.26	0.22
Midsize	0.311	0.311	0.311	0.307	0.303	0.298	0.2835	0.2715	0.285	0.26	0.24	0.28	0.25	0.22
Small SUV	0.356	0.356	0.356	0.349	0.341	0.373	0.3445	0.3305	0.39	0.34	0.32	0.37	0.33	0.3
Midsize SUV	0.366	0.366	0.366	0.38	0.37	0.383	0.375	0.36	0.4	0.37	0.35	0.39	0.35	0.33
Pickup	0.44	0.44	0.44	0.425	0.41	0.435	0.4175	0.405	0.43	0.41	0.4	0.42	0.4	0.39

It can also be seen that the drag coefficient of the different classification of vehicles reduce by about 13% - 32% by 2045 when compared to the reference year in 2010.

4 POWERTRAIN SELECTION

Among the powertrain options available, the following are selected for EDVs:

- Single-mode power-split HEV with fixed gear ratio (HEV, PHEV25)
- Series-split (GM Volt Generation [Gen] 1) configuration (PHEV50)
- Series fuel cell
- Electric drive with two-speed gearbox and fixed gear ratio for BEV (100 AER, 200 AER, and 300 AER)

The reference conventional vehicle is composed of an ICE coupled with a multi-speed automatic transmission. The power-split configuration is composed of one or multiple planetary gear sets. The HEV and PHEV25 degree of electrification is modeled as an input split with two planetary gear sets (similar to Toyota and Ford systems); the PHEV50 uses a series/output split with one planetary gear set with clutches (similar to GM Volt gen 1). A fuel-cell HEV as well as pure BEV are also modeled.

Vehicles driven solely by electrical power have been modeled with two-speed gearboxes. This choice is made to reach the vehicle maximum-speed requirement of at least 100 mph. The transmission also allows an increase in the powertrain efficiency.

4.1 HYBRID ELECTRIC VEHICLES

4.1.1 Characteristics

Hybrid electric vehicles are powered by at least two different sources of energy. In general, they combine an electrical storage system (battery, ultra-capacitor, etc.) and a heat engine. The idea behind HEVs is to combine the advantages of conventional vehicles and BEVs thereby limiting the drawbacks of each. Electric vehicles have higher efficiency, owing to the high electric machine efficiency (usually above 80% average on any cycle) and low battery losses. Furthermore, they can recover part of the energy that is lost during deceleration. For BEVs, batteries are the critical component due to their cost and life.

HEVs offer the following features:

- **Idling stop.** The engine is turned off at zero vehicle speed to avoid idling. The engine is then started using the electric machine. Depending on the electrical power available, the engine starts as soon as the vehicle moves (low power) or at higher vehicle speeds (high power).

- **Energy recovery through braking (regenerative braking).** The energy that is usually wasted by friction during deceleration can be recovered as electrical energy through an electric machine. This process is called regenerative braking, as it regenerates a part of the energy that the vehicle had to provide to overcome the effect of inertia when accelerating.

- **Electric only propulsion.** When the electric machine and the battery have sufficient power and energy, they can be used to propel the vehicle in particular to avoid operating the engine at low load and efficiency.

- **Electric machine assist.** At high power demand (i.e., when accelerating), the electric machine can assist the engine, allowing downsizing of the engine along with improved powertrain efficiency and lower transients and emissions.

All of the features mentioned above are not available for the various configurations of HEVs and depend on the powertrain configurations considered.

4.1.2 Primary Powertrain Configurations

The electrified powertrain configurations can be classified by their hybridization degree as shown in Figure 4.1. The hybridization degree is defined as the percentage of total power that can be delivered electrically. The higher the hybridization degree, the greater the ability to propel the vehicle using electrical energy.

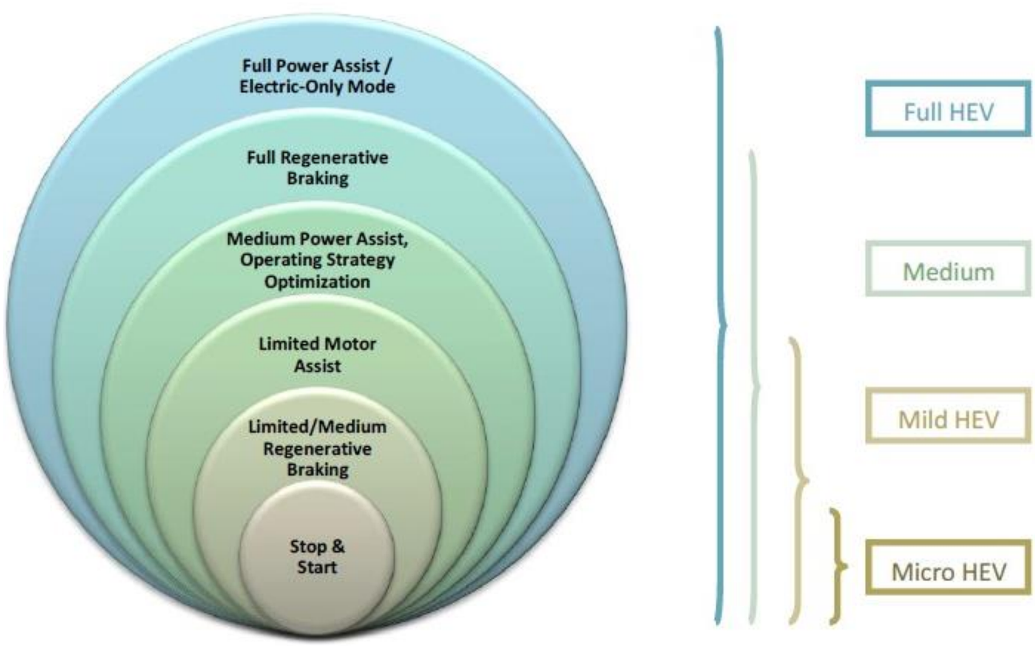

FIGURE 4.1 Hybridization degrees for HEVs

The different powertrain configurations considered in this study are:

1. Series configuration

The first HEVs were generally based on a series configuration. In this case, the vehicle is propelled solely by electrical energy. When an engine is used, it provides a generator with mechanical power, which then converts it into electricity. In the case of a fuel-cell system, the electrical energy is directly used by the electric machine. The main advantage is that the engine speed is decoupled from the vehicle speed, allowing an operating condition at or close to its most efficient operating point. The main drawback is that the main components have to be oversized to be able to maintain the same performance, which leads to higher vehicle weight.

2. Parallel configuration

In a parallel configuration, the vehicle can be directly propelled by either electrical or mechanical power. Direct connection between the energy sources and the wheels leads to lower powertrain losses compared with the pure series configuration. However, since all of the components' speeds are linked to the vehicle's speed, the engine cannot constantly be operated close to its best efficiency curve. Several subcategories exist within the parallel configuration:

- Start-stop: A small electric machine is used to turn the engine off when the vehicle is stopped.

- Starter-alternator: This configuration is based on a small electric machine (usually 5 kW to 15 kW) located between the engine and the transmission. Because of the low electric-machine power, this configuration is mostly focused on reducing consumption by eliminating idling. While some energy can be recuperated through regenerative braking, most of the negative electric-machine torque available is usually used to absorb the engine's negative torque.

- Pre- and post-transmission: Both configurations allow the driver to propel the vehicle in electric-only mode as well as recover energy through regenerative braking. The electric-machine power usually ranges from 20 kW to 50 kW. The main difference between these two options is the location of the electric machine (before or after the transmission). The post-transmission configuration has the advantage of maximizing the regenerative energy path by avoiding transmission losses. On the other hand, the pre-transmission configuration can take advantage of different gear ratios that allow the electric machine to operate at higher efficiency and provide high torque for a longer operating range.

3. Power-split configuration

The power-split configuration, composed of an engine and two electric machines, allows both parallel and series paths. The main feature is that all component speeds are decoupled, which allows a higher degree of control.

It is important to note that many different variations exist within each configuration (e.g., power-split configurations can be single-mode, two-mode, or three-mode) and among configurations (i.e., several configurations are considered to be a mix of series, parallel, and/or power-split). Overall, several hundred configurations are feasible for electric-drive vehicles (EDVs).

4.2 PLUG-IN HYBRID ELECTRIC VEHICLES

4.2.1 Definition and Characteristics

A plug-in hybrid is an HEV with batteries that can be charged from a wall outlet. The energy storage system can be plugged into an external power grid. Because of their outlet recharging capability, PHEV batteries have a lower power-to-energy ratio compared to their HEV counterparts (the increase in energy capacity for PHEV batteries vs. HEV batteries is more substantial than the increase in power requirements for PHEV batteries vs. HEV batteries). Their higher energy and power allow extended use of the electric-only mode, leading to fewer engine on/off cycles. While the engine of most midsize HEVs is started at a power demand of about 7 kW to 9 kW at the wheel, the engine of a PHEV offers the ability to start at a higher power demand, depending on the available energy and state of charge (SOC) of the battery, and the trip distance.

Because of their ability to operate primarily in all-electric mode, PHEVs offer a very promising solution to conventional fuel displacement. PHEVs share many of the powertrain components with HEVs. However, the vehicle’s ability to operate in electric mode requires different energy storage system technology and power electronics compared to HEVs:

- **Higher energy.** The batteries have higher capacity and discharge range as a function of AER.

- **Higher power.** The electric system is, in general, more powerful to enable propelling the vehicle under more aggressive driving conditions in EV mode.

- **Increased control freedom.** The higher degree of hybridization allows a greater number of possible electric machine/engine-power combinations, leading to significant added complexity in determining the optimal vehicle level control strategy compared with HEVs.

<u>PHEV operational modes:</u>

- **Charge Depleting (CD mode)**: CD mode refers to a mode in vehicle operation when the battery pack solely drives the energy requirement of the vehicle. During this operation, the battery SOC may fluctuate but it decreases on average while driving.

- **Charge Sustaining (CS mode)**: CS mode refers to a mode when the battery SOC may fluctuate but it is maintained at a certain level while driving by turning the engine on and off.

5 VEHICLE-LEVEL CONTROL STRATEGIES

The vehicle-level control strategies used for the powertrains described in the previous sections have been developed over the past 20 years (Pasquier et al. 2001; Pagerit et al. 2005; Sharer et al. 2008; Cao 2007; Karbowski et al. 2006). The vehicle-level control strategies have also been validated through generic processes developed over the years. The development of the generic process is illustrated in figure 5.1.

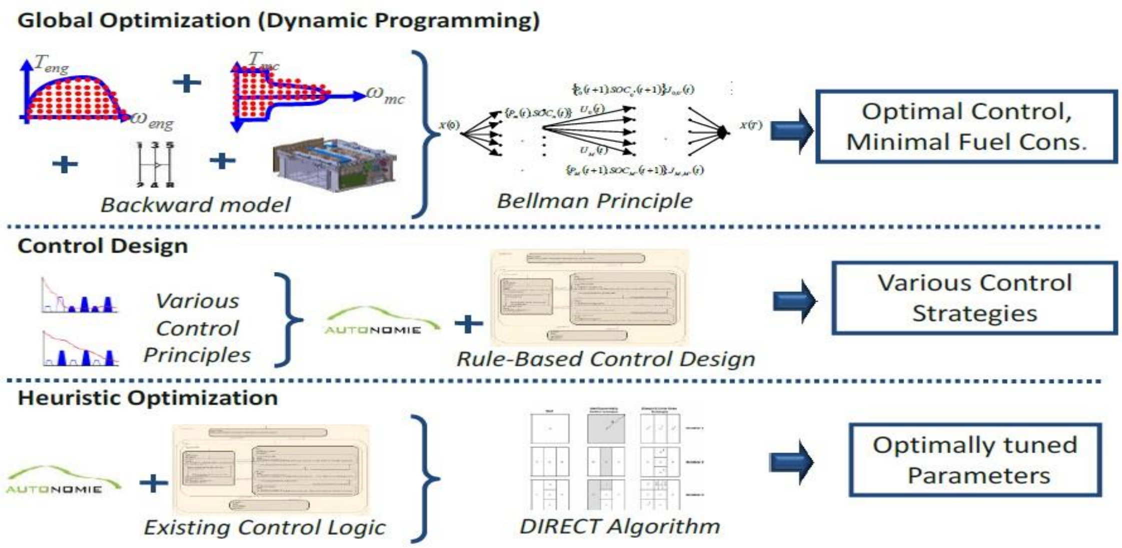

FIGURE 5.1 Vehicle-level control strategy development

- **Global optimization.** The objective of this step is to define the main rules (Karbowski et al. 2006). For example, the engine turns on based on the SOC of the battery, vehicle speed, and the wheel torque demand.

- **Control Design.** The rules defined in this optimization step are implemented into an algorithm (generally SimuLink and StateFlow) and exercised to make sure they operate properly.

- **Heuristic optimization.** This step defines the values of the parameters in the main control strategy, such as the engine turn on condition for a specific SOC and wheel torque demand. The process uses the DIRECT (DIviding RECTangles) algorithm to define the parameters automatically.

6 VEHICLE DEFINITION

6.1 VEHICLE TECHNICAL SPECIFICATION

The generic vehicle sizing requirements are outlined below:

- Initial vehicle movement (IVM) to 60 mph at less than 8.5 seconds.
- Maximum grade of 6% at 65 mph at gross vehicle weight (GVW).
- Maximum vehicle speed >100 mph.

The outlined requirements are a good representation of the current American automotive market, as well as expectations of American drivers. A relationship between the vehicle curb weight and GVW have been developed using current vehicles to verify that the grade requirements have been met.

6.2 POWERTRAIN SIZING ALGORITHMS

Due to the limited feasibility of sizing individual vehicle components, a generic P/W ratio is maintained across the different powertrains that are sized. An inconsistency in the different technologies results from the impact of component maximum torque curves. As a result, each vehicle is sized independently to meet specific VTS.

Incorrect sizing of the components leads to differences in both energy consumption and cost, and will influence the results accordingly.

On this basis, several automated sizing algorithms have been developed to provide a fair comparison between technologies. The different algorithms have been defined depending on the powertrain (i.e., conventional, power-split, series, electric) and the application (i.e., HEV, PHEV).

All sizing algorithms follow the same concept: the vehicle is built from the bottom up, meaning each component assumption (specific power, efficiency, etc.) is taken into account to define the entire set of vehicle attributes (vehicle curb weight, etc.) The process is recursive in the sense that the main component characteristics (maximum power, vehicle weight, etc.) are influenced accordingly until all the VTS are met. On average, the sizing algorithm takes between 5 to 10 iterations to converge. Figure 6.1 illustrates the different processes involved to size a conventional vehicle.

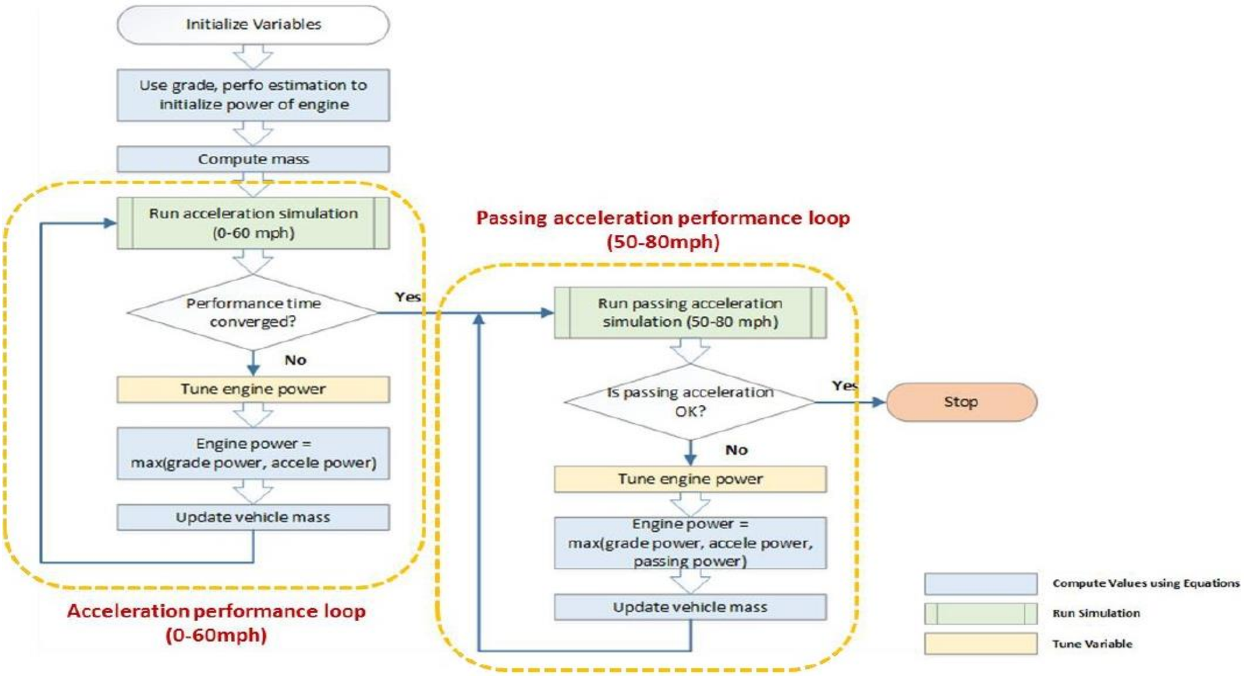

FIGURE 6.1 Conventional powertrain sizing algorithm

The sizing rules are specific to the various powertrains and applications:

- For HEVs, the electric machine and battery powers are determined to capture all the regenerative energy from a UDDS cycle. The engine and the generator are then sized to meet the gradeability and performance requirements (e.g., IVM to 60 mph).

- For PHEV25s, the electric machine and battery powers are sized to be able to follow the UDDS cycle in electric-only mode (this control is only used for the sizing; a blended approach is used to evaluate the consumption). The battery-usable energy is defined to follow the combined drive cycle for 25 miles (adjusted). The engine is then sized to meet both performance and gradeability requirements

- For PHEV40s and PHEV50s, the main electric machine and battery powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery-usable energy is defined to follow the combined drive cycle for 40 or 50 miles (adjusted), depending on the requirements. The genset (engine plus generator) or the fuel-cell systems are sized to meet the gradeability requirements.

The sizing algorithms provide the optimum component sizes, while OEMs would have to select among the available choices.

6.3 SIZING RESULTS

This section describes the maximum power, energy, and weight of the different vehicles after sizing.

6.3.1 Conventional Powertrain

The component characteristics of each vehicle class have evolved similarly. The following section presents the midsize class sizing result.

Figure 6.2 illustrates the evolution in engine peak power of conventional vehicles across different lab years and technology progress cases.

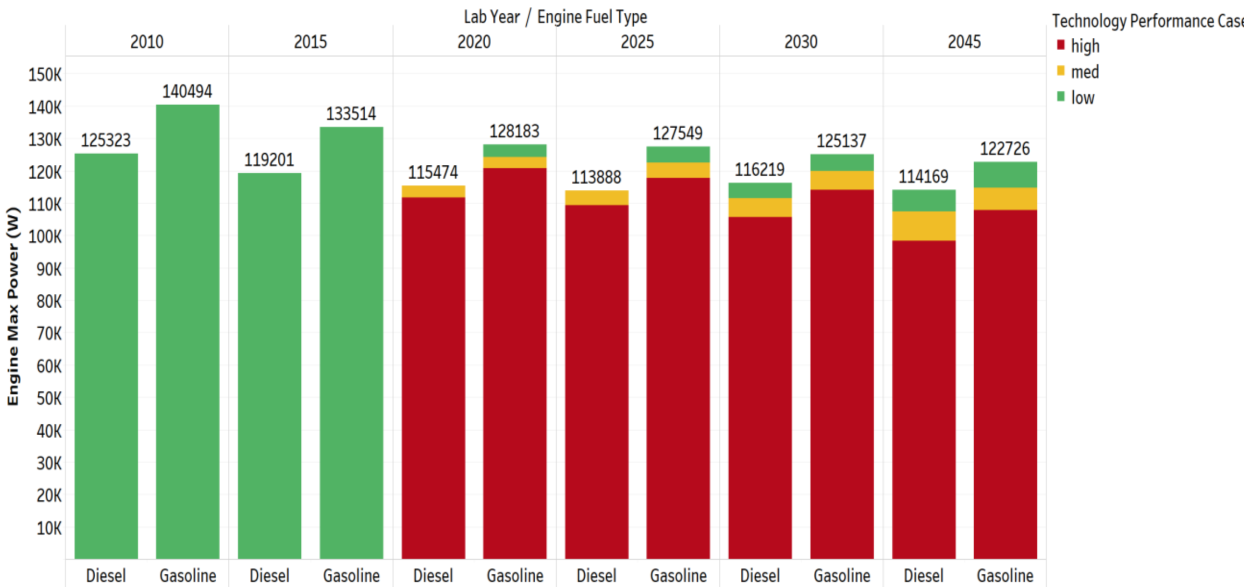

FIGURE 6.2 Conventional powertrain sizing algorithm

It can be seen that over time, the engine peak power decreases. This trend can be explained by the effects of lightweighting with time.

Figure 6.3 illustrates the overall effect of vehicle mass on the engine peak power for both diesel and gasoline fuel types.

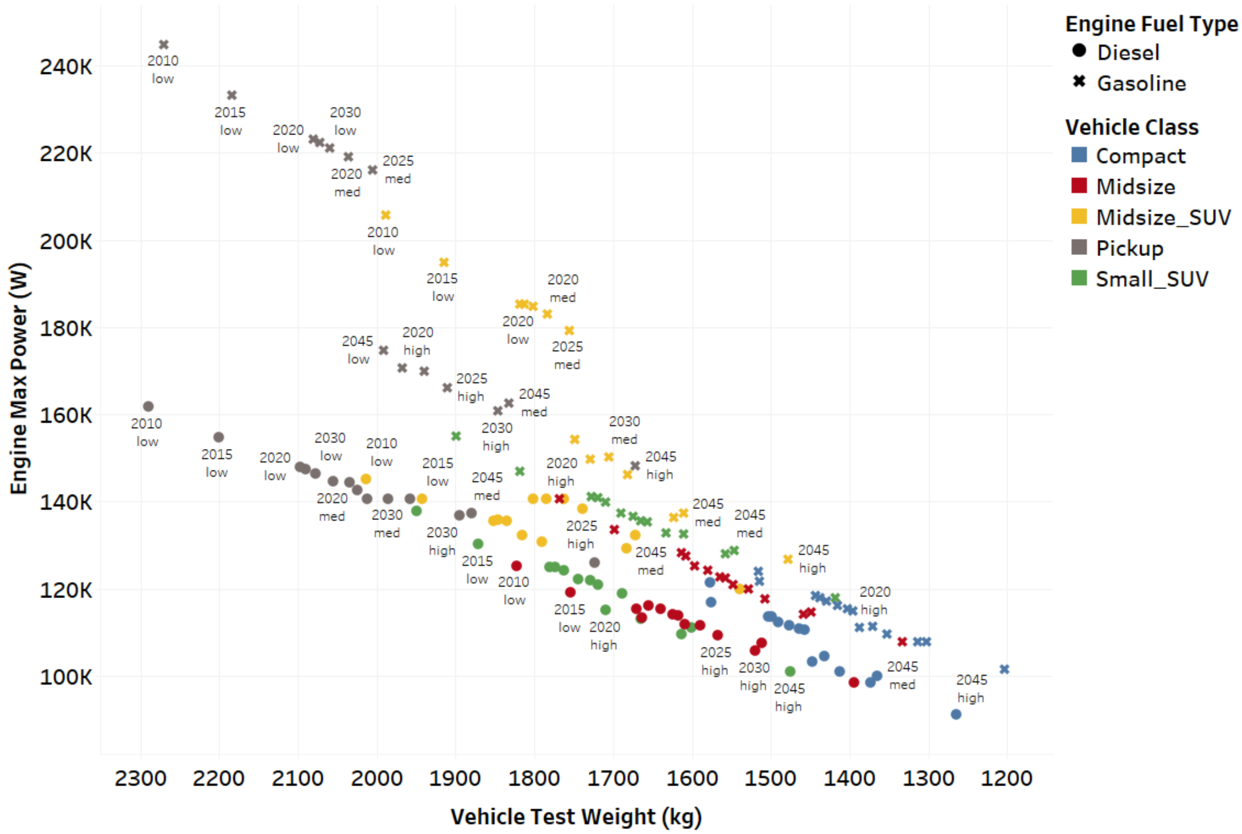

FIGURE 6.3 Engine peak power as a function of vehicle mass for conventional engines

It can be observed that engine power changes linearly with vehicle mass. The fuel order in the trend tracks the power ratios previously described. All the engine technologies cover similar mass ranges, but they do not require the same power—higher torque is present at lower engine speed for the diesel engines.

6.3.2 Split HEVs

6.3.2.1 Engine

Figure 6.4 illustrates the peak power for midsize HEVs with gasoline engines. The engine power for HEVs is determined by both the performance and grade requirements. While performance is the primary factor for current technologies, future lightweighting makes gradeability requirements critical for some cases.

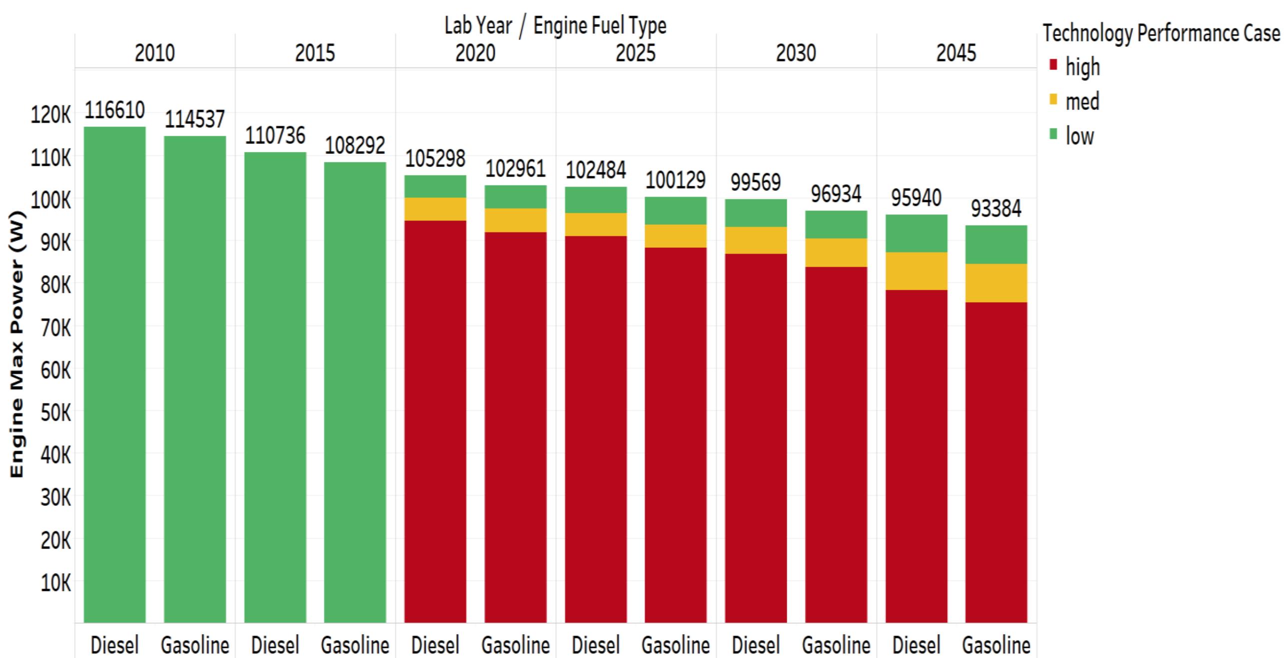

FIGURE 6.4 Engine peak power for split HEV for conventional powertrains

6.3.2.2 Electric Machine

Figure 6.5 illustrates the evolution of electric machine peak power for HEVs with different fuel types.

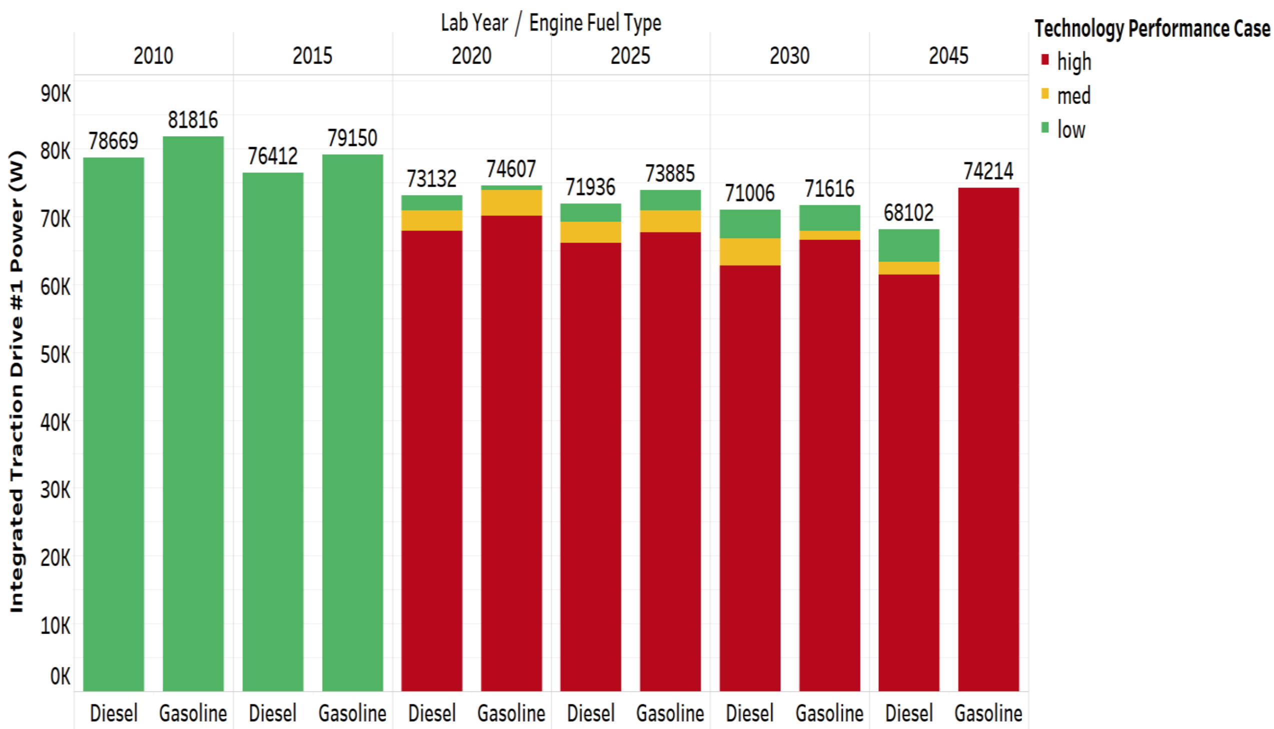

FIGURE 6.5 Electric machine power for midsize split HEVs

It can be observed that electric machine peak power decreases in the future because of the effects of lightweighting. Future lightweighting makes the gradeability requirements critical for some cases, and hence the 2045 high case contains an electric machine with a higher peak power than the low or medium cases.

6.3.2.3 Battery

Figure 6.6 illustrates the HEV battery power. The powers are determined to capture the entire energy during deceleration on the UDDS drive cycle. Future lightweighting and increased component efficiencies contribute to lower battery peak power.

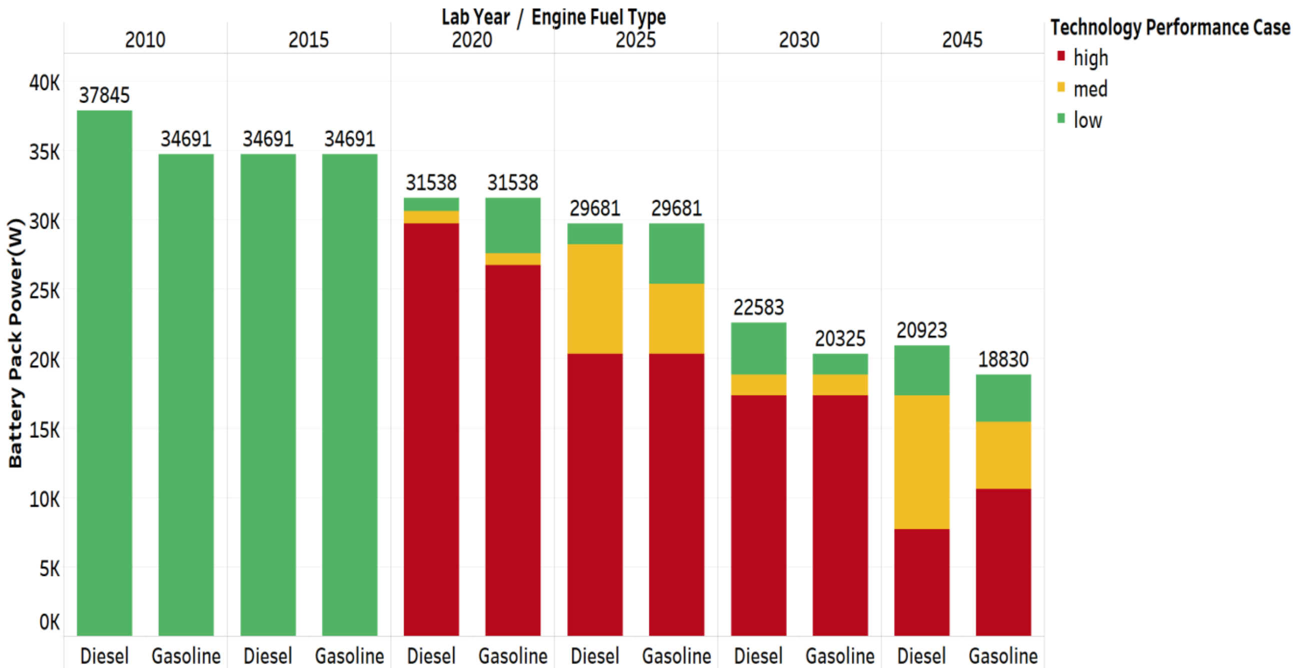

FIGURE 6.6 Battery power for midsize split HEVs

The variation in the reduction of battery power requirements across different lab years can be explained by the combined effects of lightweighting as well various vehicle component efficiency improvements.

6.3.3 Plug-In HEVs

6.3.3.1 Engine

Figure 6.7 shows the gasoline-engine peak power for the various PHEV powertrains and timeframes. Due to the large electric machine, the engines are all sized to provide acceptable gradeability.

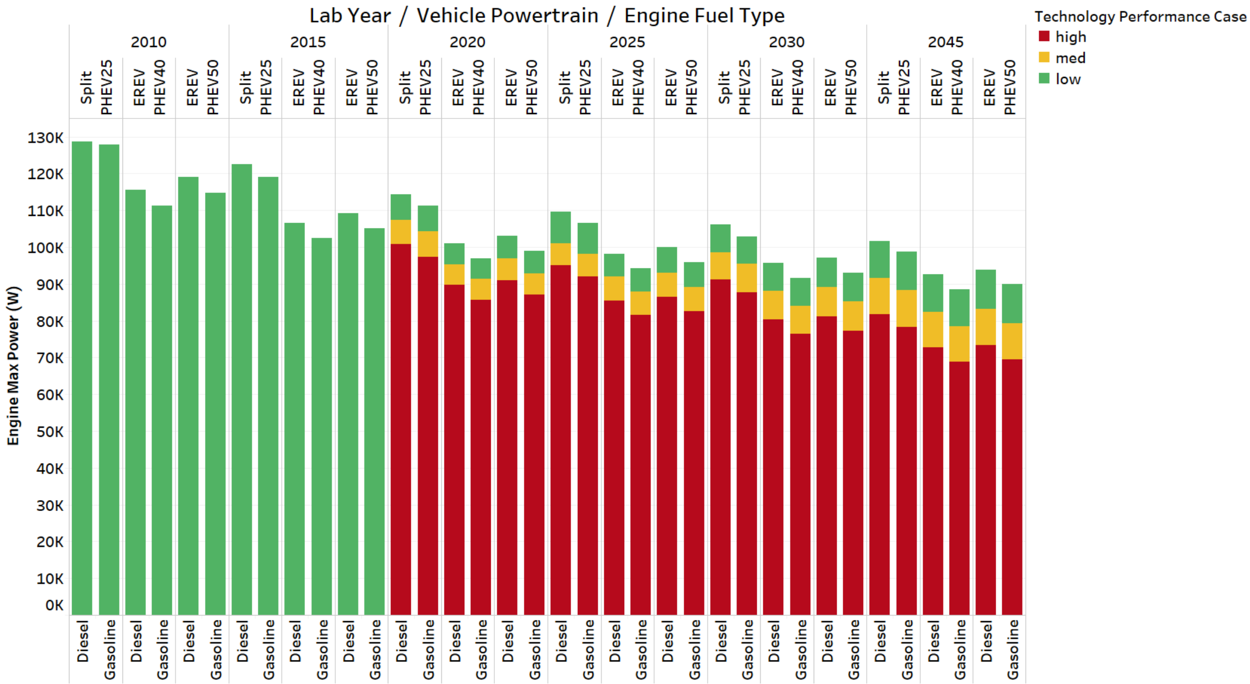

FIGURE 6.7 Engine peak power for midsize PHEV powertrains across range classifications

6.3.3.2 Electric Machine

Figure 6.8 illustrates the peak power of the different electric machines for the PHEVs. The electric machines for the PHEV25 cases are sized so the vehicle is capable of following the UDDS drive cycles in electric mode. The electric machines for the PHEV40 and PHEV50 cases are sized to allow the vehicles to follow the US06 drive cycle.

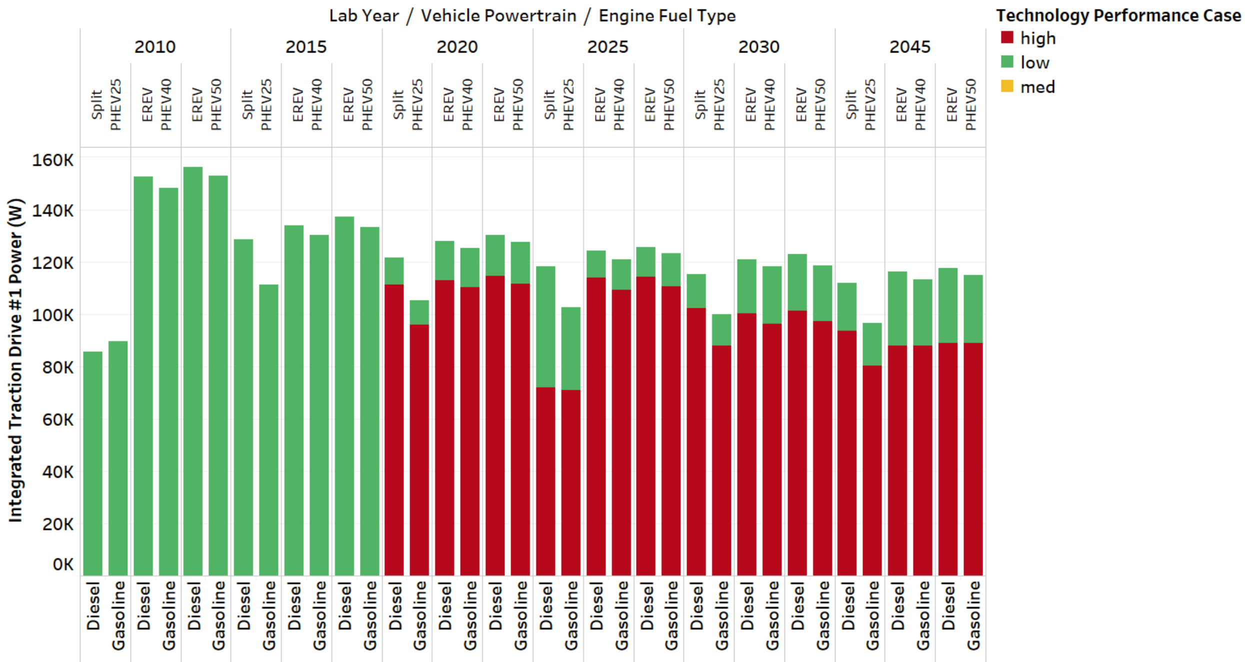

FIGURE 6.8 Electric machine peak power for midsize PHEV powertrains across range classifications

The technology R&D leads to power reductions ranging from 17% to 30% by 2045 for PHEV25 AER, 23% to 40% for PHEV40 AER, and 27% to 55% for PHEV50 AER (gasoline).

6.3.3.3 Battery

Figure 6.9 illustrates the battery pack power for the different PHEV powertrains across the specified timeframes.

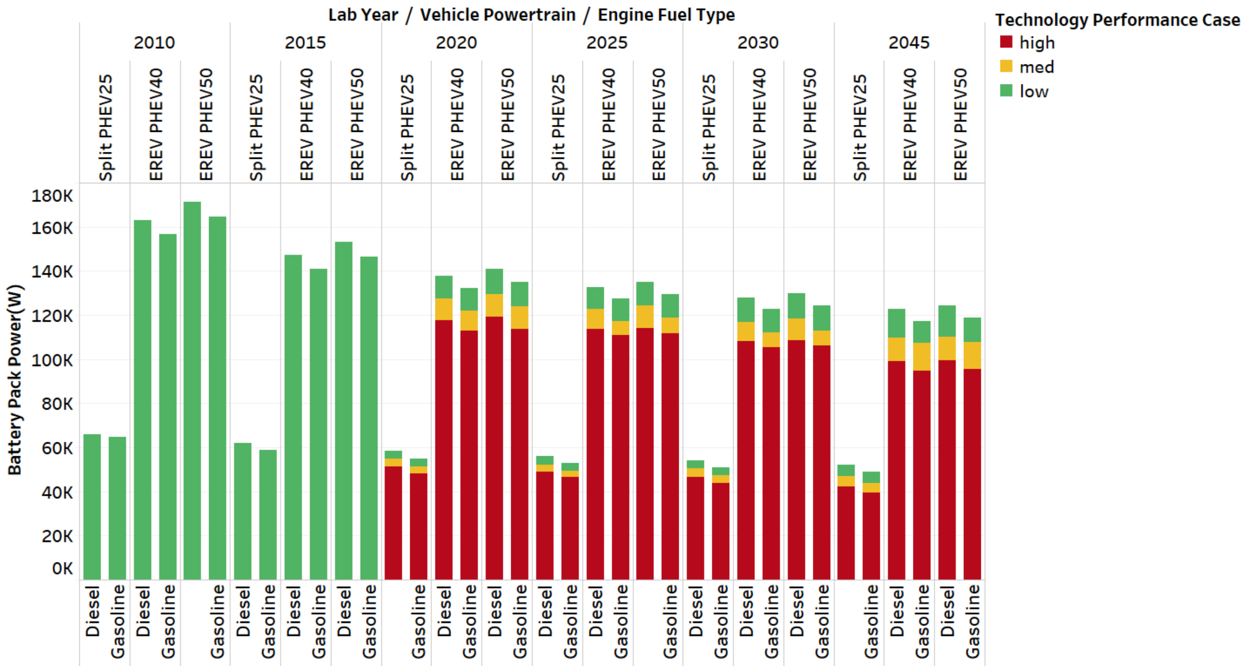

FIGURE 6.9 Battery pack power for midsize PHEV powertrains across range classifications

The results show the battery pack power decreases by 26% over time for the PHEV25, and by nearly 30% for the PHEV40 and PHEV50. The battery for PHEV40 and PHEV50, sized for the US06 cycle in electric only mode, has nearly three times more power than the PHEV25. From one AER to the next, the battery power increases by an average of 3% for E-REV powertrains.

6.3.4 Fuel-cell HEV/PHEVs

Fuel-cell systems show a decrease in fuel-cell peak power over time owing to vehicle lightweighting and better fuel efficiency. The total decrease from the reference case to the 2045 case ranges between 20% and 45% for fuel-cell HEVs, and between 21% and 40% for fuel-cell PHEVs. The comparisons refer to midsize vehicle class.

Figure 6.10 illustrates the fuel cell peak power for midsize vehicles.

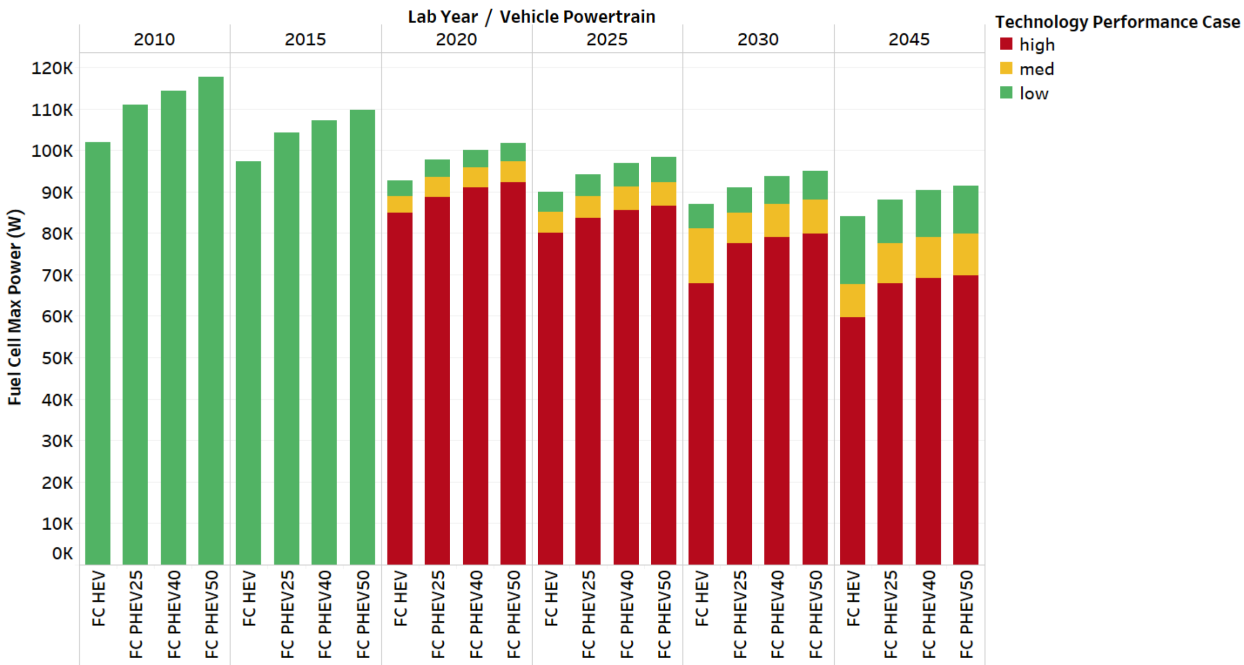

FIGURE 6.10 Fuel-cell system power for midsize fuel-cell HEVs

6.3.5 Battery Electric Vehicle

Figure 6.11 shows the electric machine peak power for the different BEVs of midsize vehicle class.

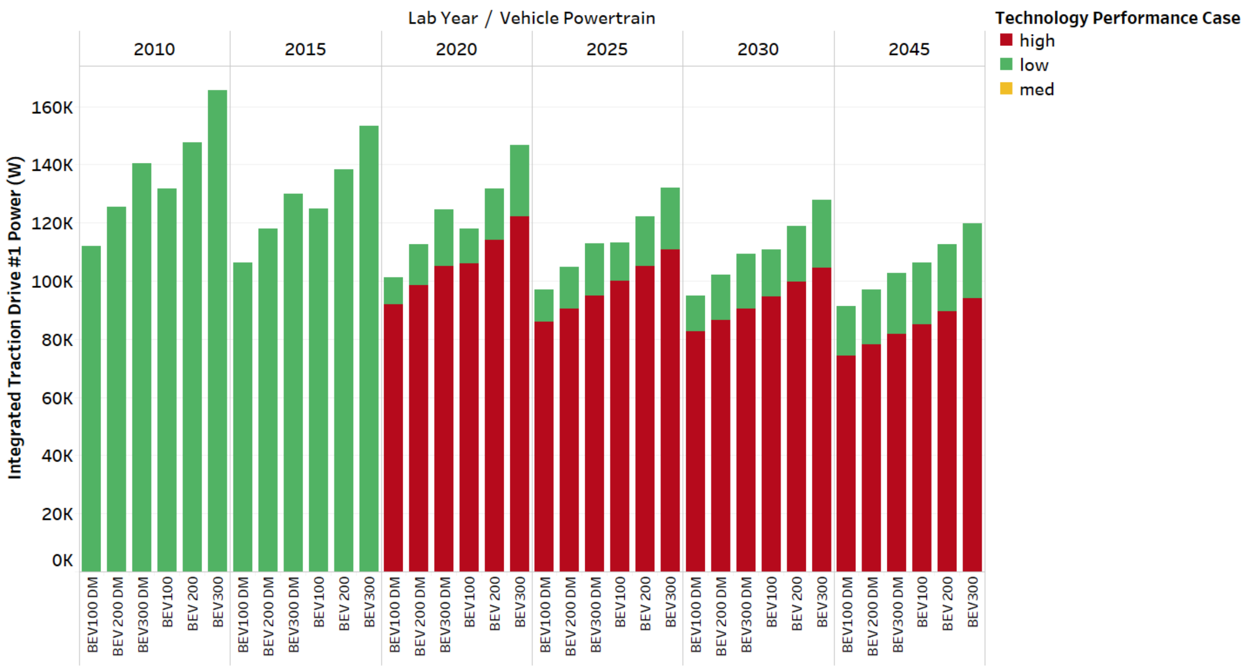

FIGURE 6.11 Electric machine power for midsize BEVs across powertrains

It can be seen that electric machine peak power requirements decrease over time owing to lightweighting and assumptions in electric machine efficiency improvements. The decrease ranges between 22% and 38% for BEV100, between 24% and 39% for BEV200, and between 28% and 44% for BEV300.

Figure 6.12 shows the battery pack power for the different midsize BEV powertrains across the timeframes.

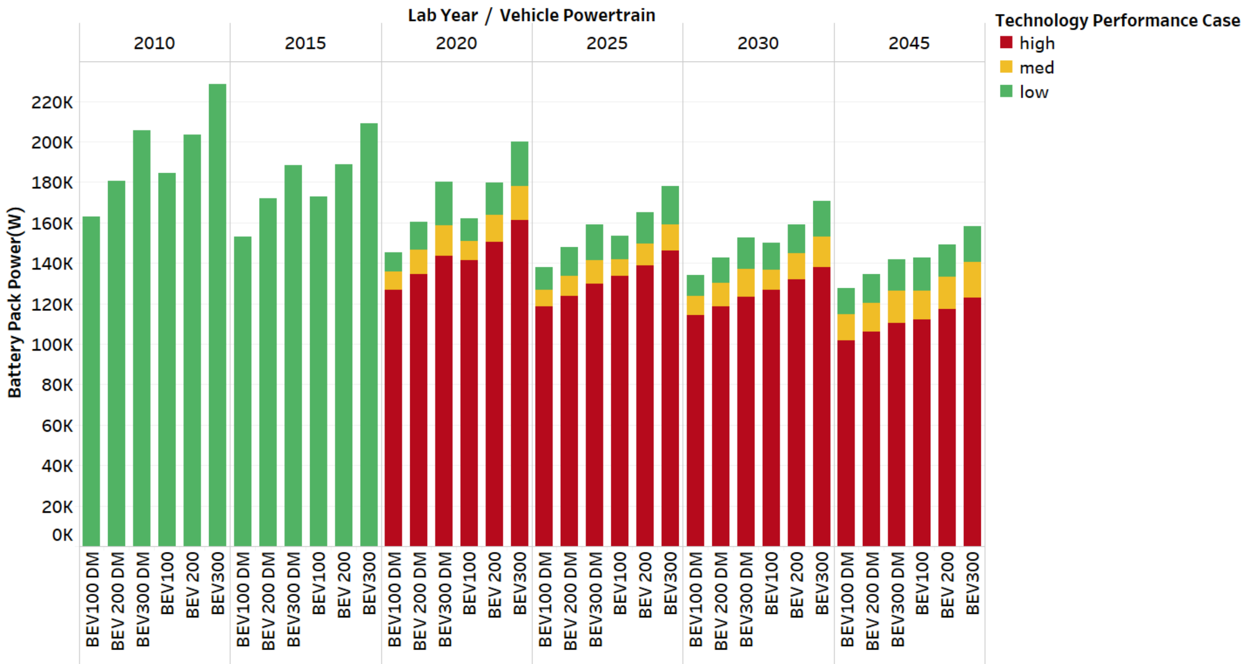

FIGURE 6.12 Battery pack power for midsize BEVs across powertrains

It can be concluded that both the electric machine and the battery are close to 50% less powerful by 2045 compared with the reference case in 2010. This can be explained due to the impact of lightweighting as well as the combined effect of improved vehicle component assumptions. With the lightweighting and advancement in technologies, the same performance could be achieved with a much smaller battery size and hence the sizing logic results in less powerful electric machines and batteries in the future when compared to the reference case in 2010.

7 TEST PROCEDURE AND CONSUMPTION CALCULATIONS

A two-cycle test procedure is used based on the UDDS and HWFET drive cycles. The calculations reflect the latest Environmental Protection Agency (EPA) test procedures. Unless otherwise stated, the energy consumption values reported reflect the combined unadjusted values from the simulation runs. Unadjusted values reflect the simulation results without any EPA adjustment factors and the combined values follow the calculation:

$$Combined = 0.55 \times UDDS + 0.45 \times HWFET$$

All the simulations are performed under hot conditions. The cold-start penalties are assessed after simulations based on test data collected at Argonne's APRF and a literature search.

Table 7.1 summarizes the cold-start penalties applied to the UDDS CS results for the different powertrains.

TABLE 7.1 Cold-start penalties for the different powertrain configurations (%)

Powertrain	2010 Ref	Low	2015–2045 Medium	High
Conventional	12	12	10	6
Power-split HEV	12	12	10	6
Power-split PHEV (25 AER in CS only)	12	12	10	6
E-REV PHEV (40 and 50 AER in CS only)	12	12	10	6
Fuel-cell HEV	0	0	0	0
Fuel-cell PHEV	0	0	0	0

Table 7.2 summarizes the fuel properties used for simulation in Autonomie.

TABLE 7.2 Fuel properties in Autonomie simulation

	Energy density (MJ/kg)	Volumetric density (kg/L)
Gasoline	43.1	0.741
Diesel	42.5	0.835

8 ENERGY CONSUMPTION RESULTS

The fuel consumption results in the report are expressed in liters per 100km (l/100km). Unless otherwise specified, all the fuel consumption results are provided for a combined drive cycle using unadjusted values based on gasoline equivalent.

The results in this section represent the midsize vehicle class only, though the simulations are done for all vehicle classes.

8.1 EVOLUTION OF SPECIFIC POWERTRAIN CONFIGURATIONS

8.1.1 Conventional Powertrain

The evolution in fuel consumption for the midsize conventional powertrain for gasoline and diesel fuel types is expressed in Figure 8.1 below.

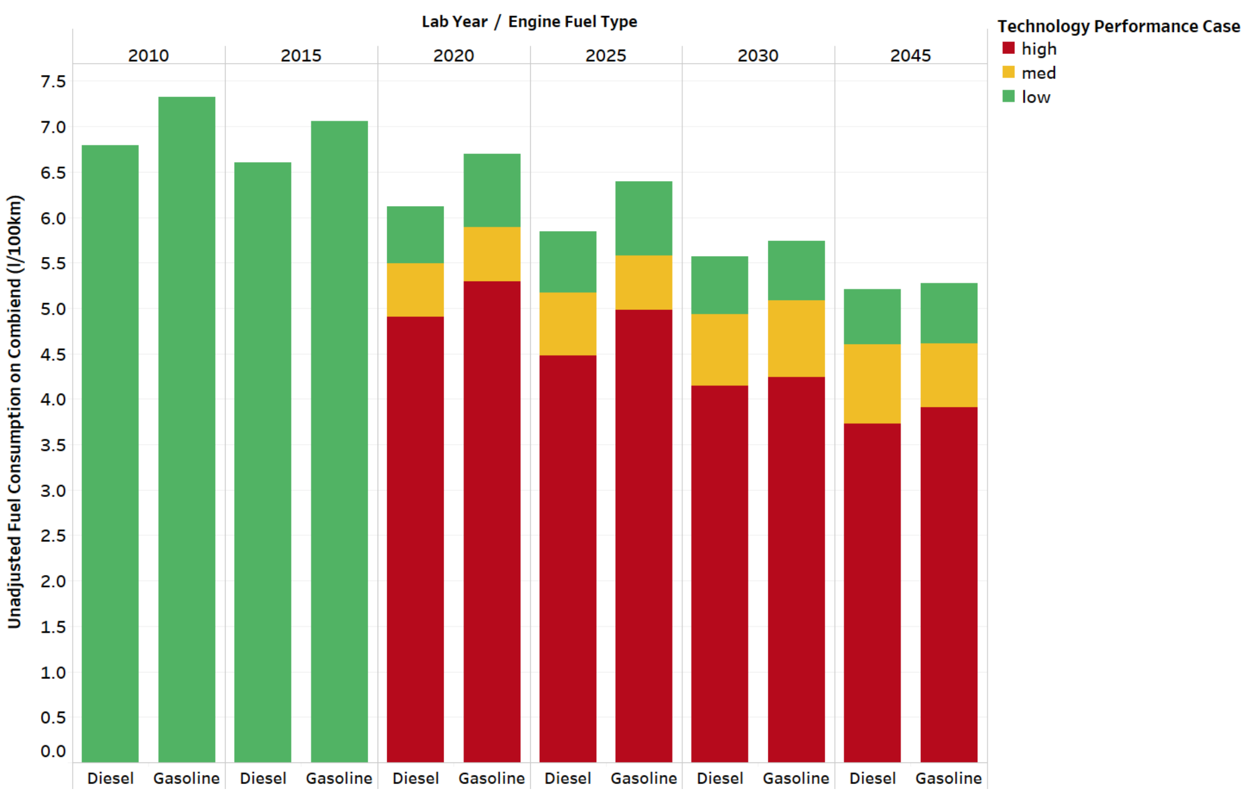

FIGURE 8.1 Unadjusted fuel consumption for conventional midsize cars

It can be observed from the plot that fuel consumption decreases over time across fuels. Gasoline conventional vehicles consume from 29% to 48% less fuel by 2045 compared with the reference (2010) lab year. Diesel powertrains evolve differently with decreases ranging from 25% to 46%.

8.1.2 Power-split HEV Engine

The evolution in fuel consumption for the midsize split HEVs for gasoline and diesel fuel types is illustrated in Figure 8.2 below.

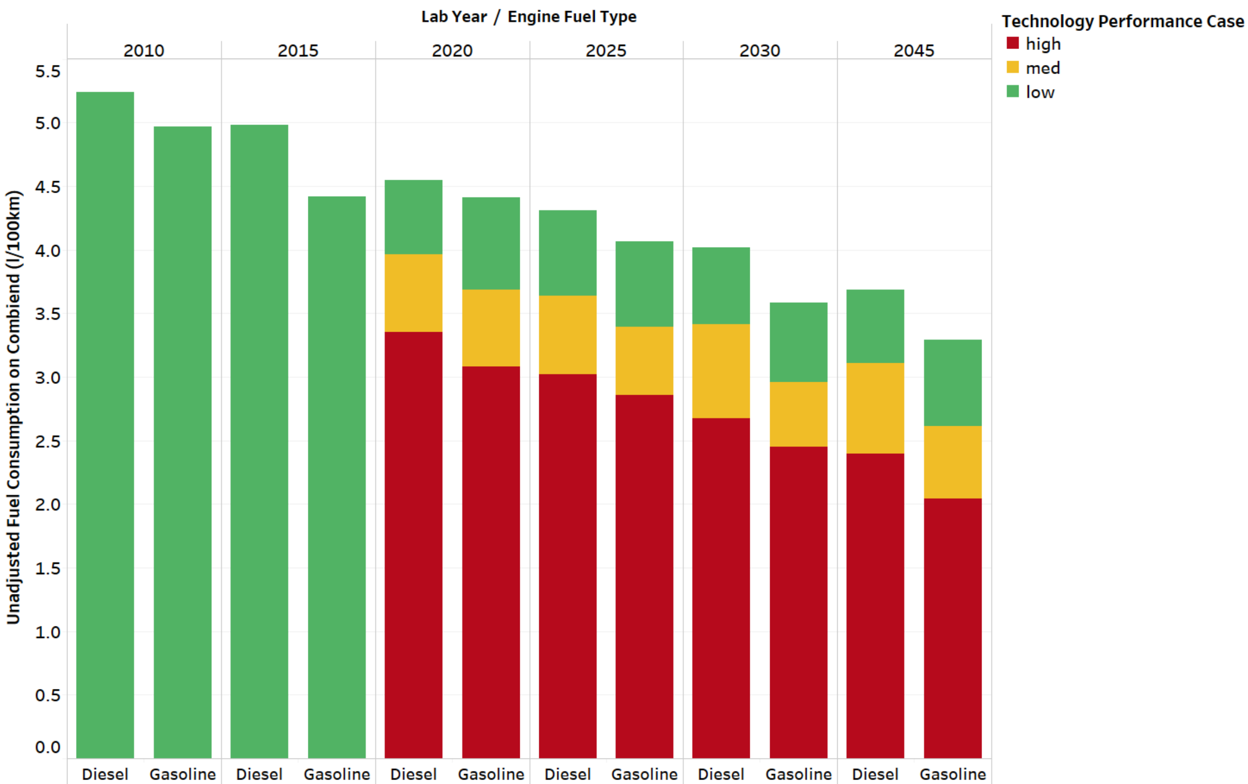

FIGURE 8.2 Unadjusted fuel consumption for midsize power-split cars

It can be observed that, similar to the conventional powertrain, the fuel consumption for HEVs is expected to decrease significantly over time. With reference to lab year 2010, the fuel consumption for gasoline vehicles decreases by 37% to 62%.

8.1.3 PHEV Engine

The gasoline-equivalent fuel consumption for midsize PHEVs is illustrated in Figure 8.3. The low, medium, and high cases represent the different technology performance cases described in Section 2.4.

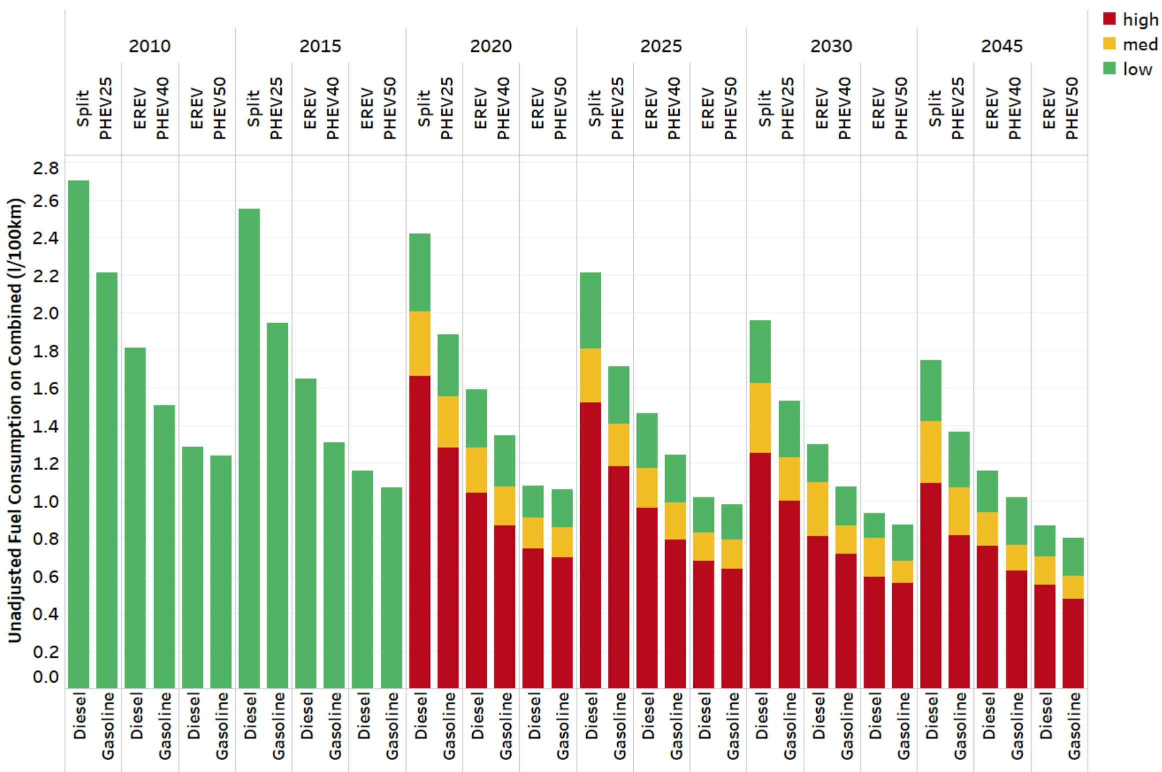

FIGURE 8.3 Unadjusted fuel consumption for midsize PHEV cars (charge-depleting and charge-sustaining modes)

The fuel consumption evolution for power-split PHEVs is similar to that of the power-split HEVs. As observed in Figure 8.3 above, the fuel economy improves with higher AER for the same fuel. This improvement is explained by the fact that the bigger the battery (for higher AER PHEVs), the less fuel is consumed. However, a trend line between the battery size and the specific fuel consumption improvement cannot be deduced. For instance, between 2010 and 2045 lab years, the fuel-consumption improvement of gasoline engines is about 39% for split PHEV25 AER, 33% for E-REV40 AER, and 34% for E-REV PHEV50 AER. These variations do not show a trend related to battery size and improvements over the years.

The electric consumption evolution for PHEVs is illustrated in Figure 8.4.

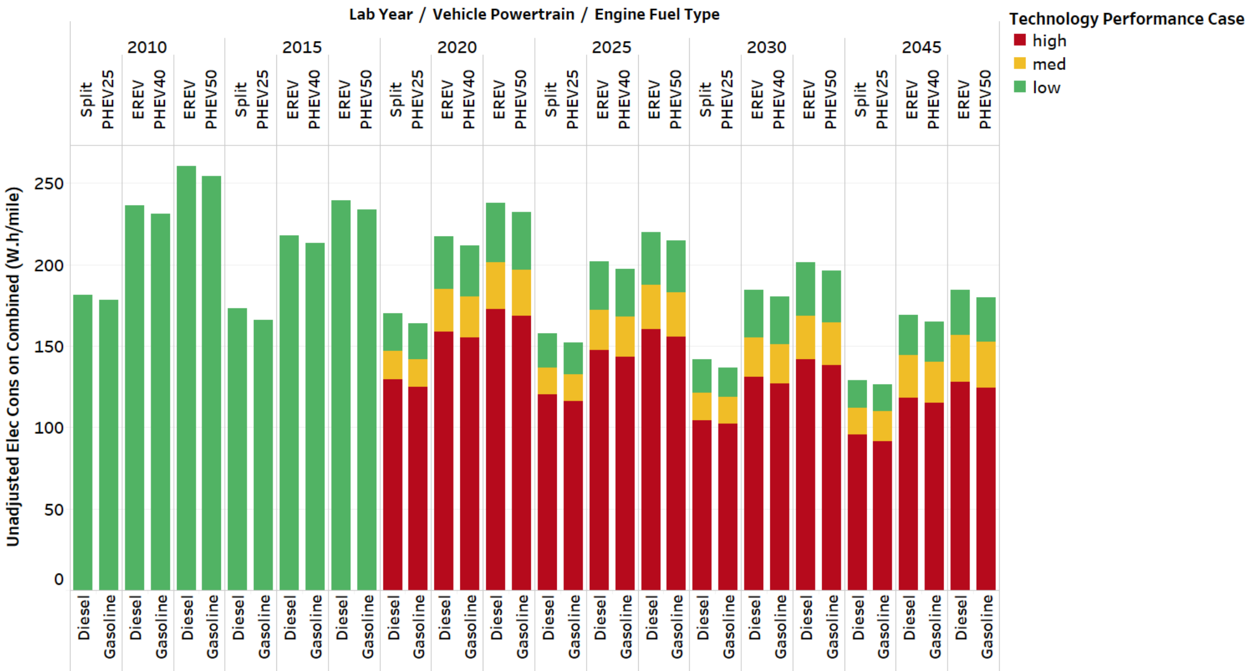

FIGURE 8.4. Unadjusted electric consumption for midsize PHEV cars on combined driving cycle

Again, the effect of the increased AER on the electrical consumption is observed, owing to bigger batteries on higher AER. Over the years, the consumption decreases significantly from higher energy densities and lightweighting along with further improvements in technologies.

8.1.4 Fuel-Cell HEVs

The evolution in unadjusted fuel consumption for the fuel-cell HEVs is illustrated in Figure 8.5 below.

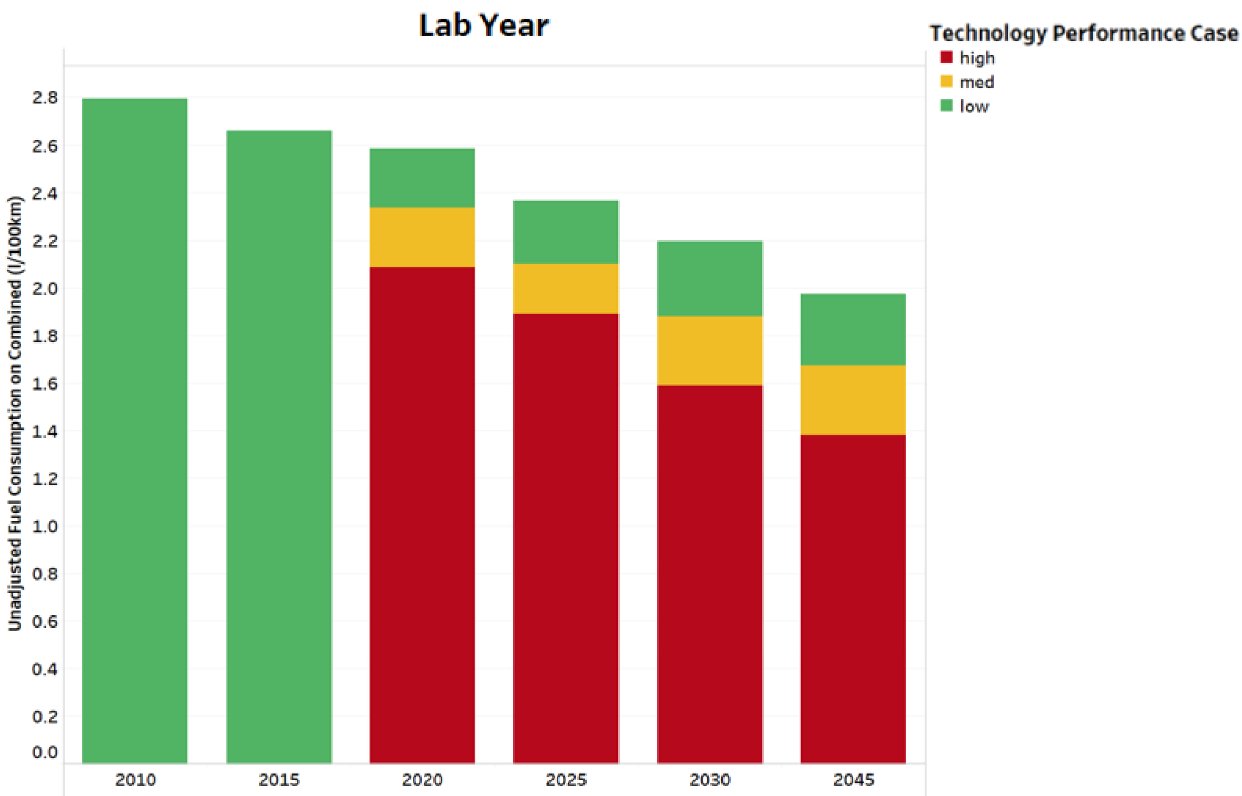

FIGURE 8.5 Unadjusted fuel consumption for midsize fuel-cell HEVs

It can be observed that the fuel consumption in 2045 is around 37% to 43% lower than the reference case of lab year 2010. This decrease is due to the advance in technology and better component efficiencies over time.

8.1.5 Fuel-Cell PHEVs

Figure 8.6 illustrates the evolution of fuel consumption for fuel-cell PHEVs. It can be observed that fuel consumption decreases slowly as AER increases to higher ranges, similar to the power-split PHEVs.

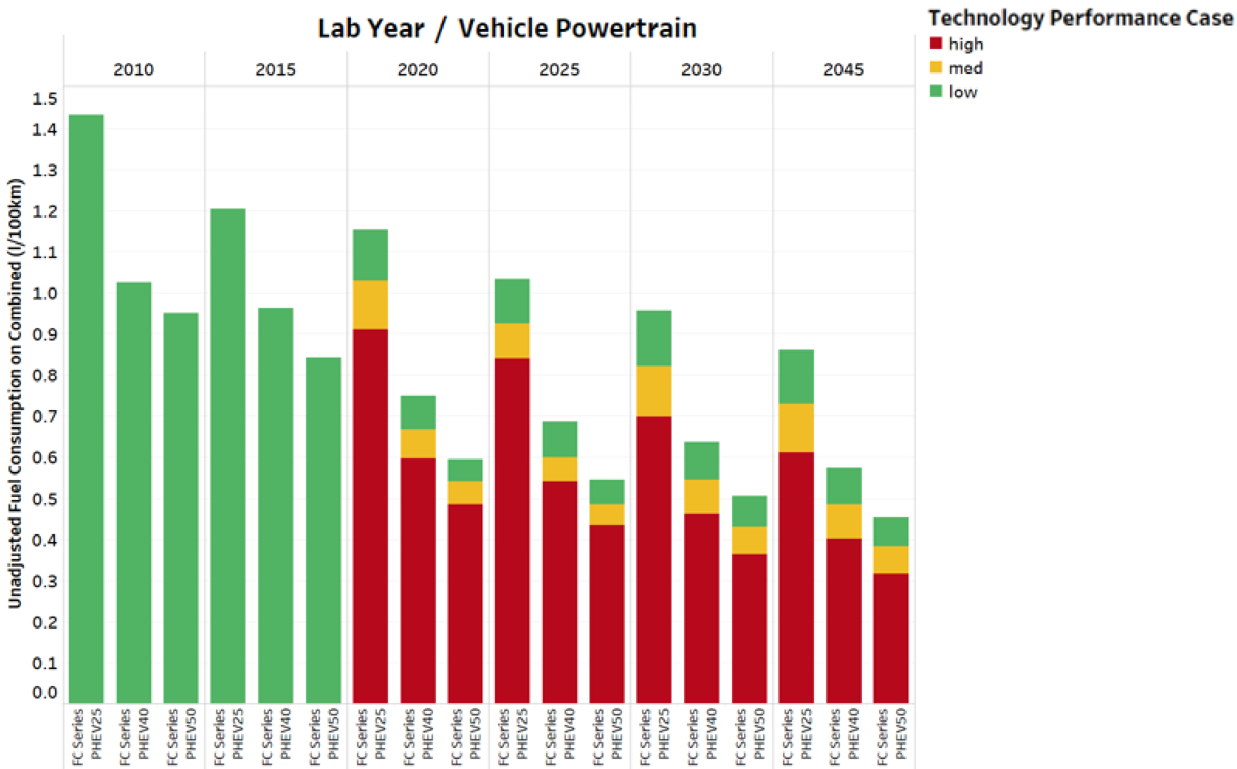

FIGURE 8.6 Unadjusted fuel consumption for midsize fuel-cell PHEVs (charge-depleting and charge-sustaining modes)

From 2010 lab year to 2045 lab year, the consumption decreases by 40% to 58% across the different AERs. This rate of change coincides with the decrease in fuel-cell HEV fuel consumption.

Figure 8.7 illustrates the evolution in electrical consumption going from lab years 2010 to 2045.

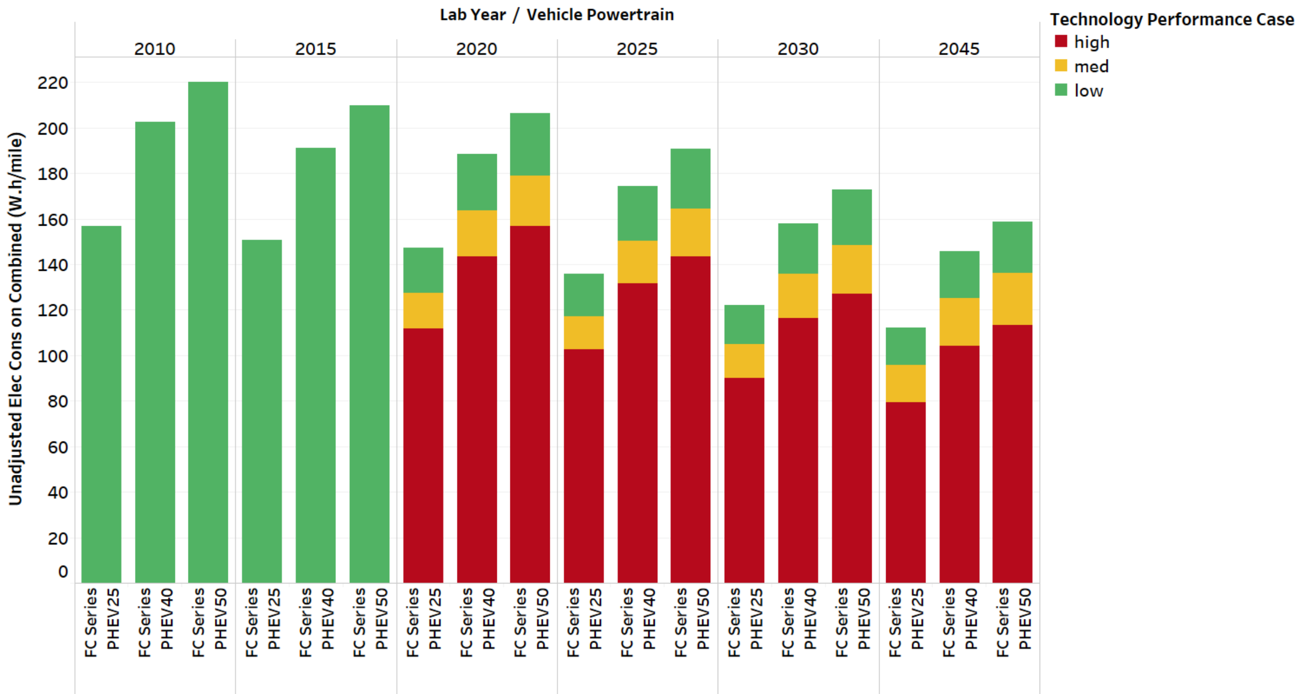

FIGURE 8.7 Unadjusted electrical consumption in charge-depleting (CD) and charge-sustaining (CS) modes for midsize fuel-cell PHEVs

It can be observed that the electrical consumption increases with AER increases, consistent with power-split PHEV consumption. These increases arise from a larger battery used for higher electrical ranges. However, the trend line decreases over time from lightweighting and advanced vehicle technologies.

8.1.6 Battery Electric Vehicles

For BEVs, the results are presented in terms of electrical consumption for the two drive cycles used in the simulations: UDDS and HWFET. Improvements in lightweighting and component sizing in future years leads to a significant decrease in electrical consumption over time.

Figure 8.8 illustrates the electrical consumption for BEV100 for a midsize vehicle. The values, expressed in Wh/mile, represent the average energy provided by the battery to drive the vehicle for 1 mile. The labels high, medium, and low represent the technology performance cases.

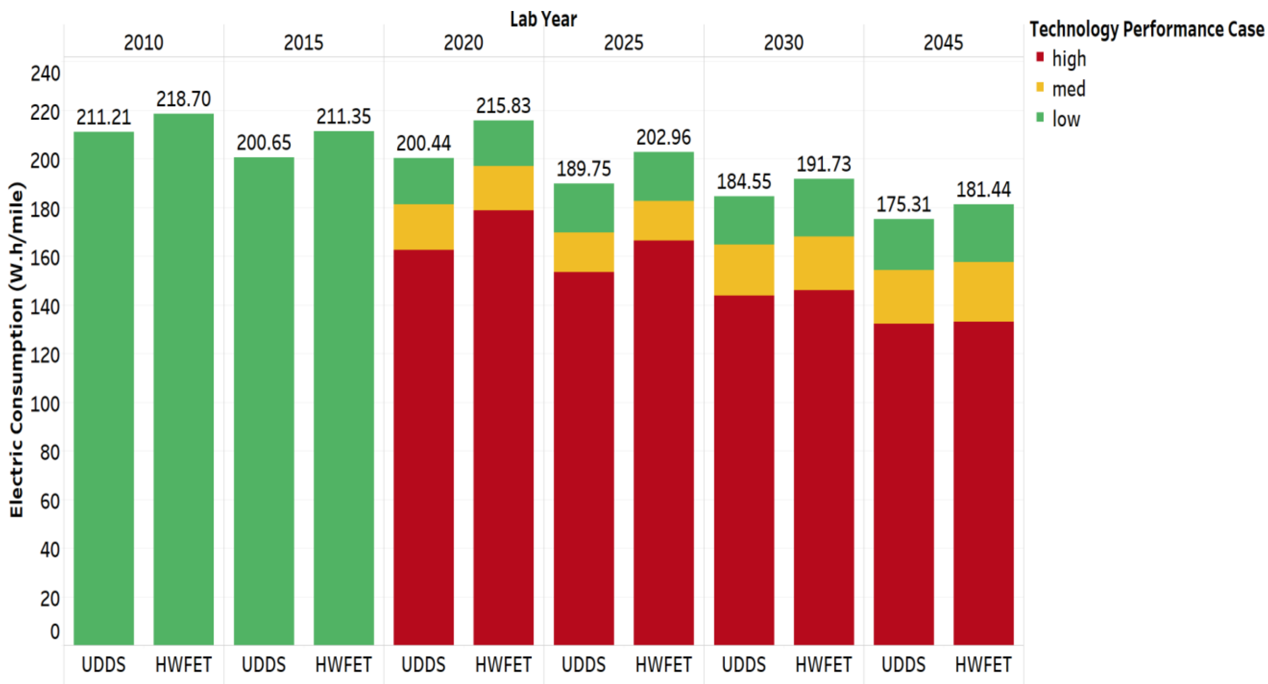

FIGURE 8.8 Unadjusted electrical energy consumption by midsize BEV100s operating on UDDS and HWFET cycles

As can be observed from the figure, the electrical consumption in HWFET cycles tends to be consistently higher than the UDDS cycles for the corresponding cases. The trend is explained by looking at the two drive-cycle curves and the energy that is recoverable by regenerative braking. The UDDS cycle consists of many strong and steep braking periods, which allows a lot of the energy to be recovered. However, the HWFET cycle consists of stable speeds and limited braking. Hence, the battery recovers more energy through regenerative braking during a UDDS cycle than a HWFET cycle. HWFET cycles also consist of higher speeds, which affect energy consumption.

The relationship between the effects of vehicle lightweighting and electrical consumption can be observed in Figure 8.9 below. The figure illustrates the electrical consumption on UDDS cycles for the different BEV powertrains simulated.

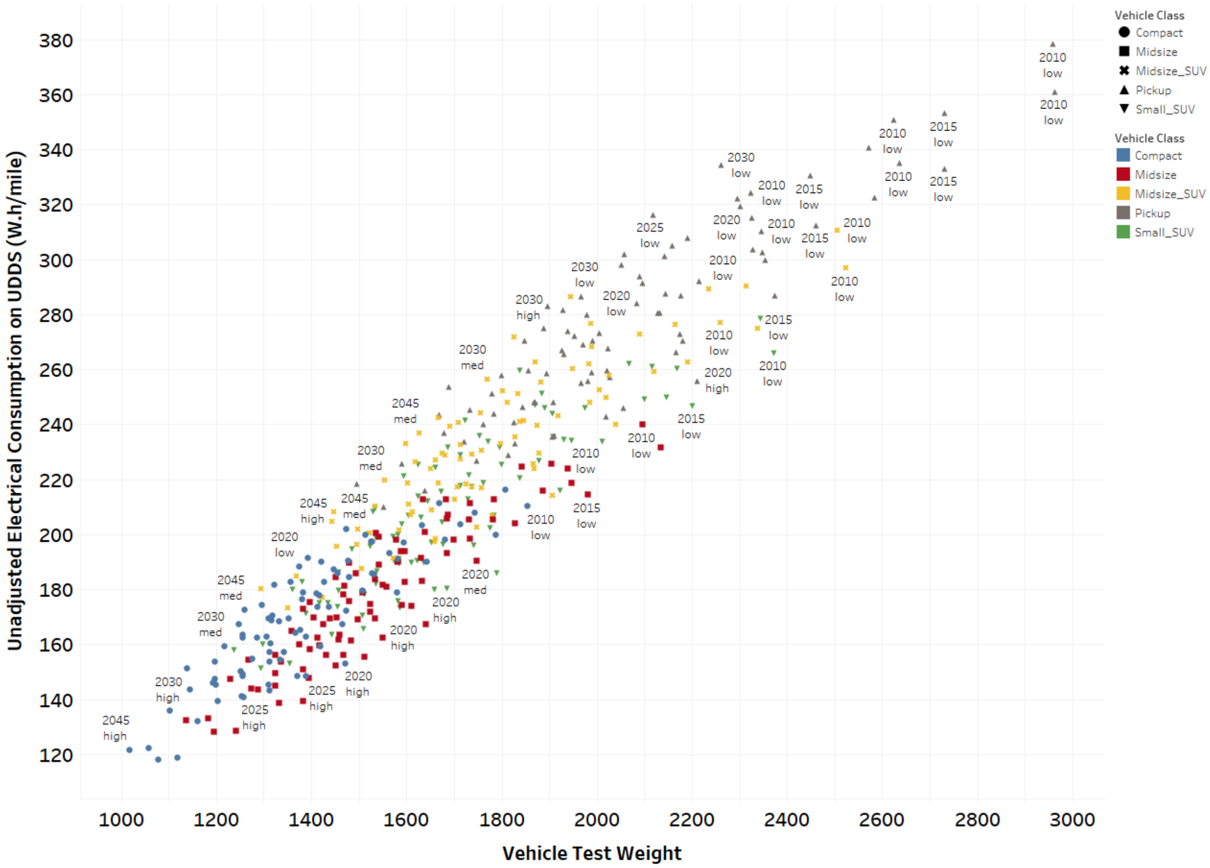

FIGURE 8.9 Electrical consumption vs. vehicle mass by vehicle class for all range BEVs

8.2 EVOLUTION OF HEV ENGINES

8.2.1 HEV vs. Conventional Engines

The comparison between midsize power-split HEVs and conventional gasoline vehicles is illustrated in Figure 8.10. The labels high, medium, and low refer to the different technology performance cases.

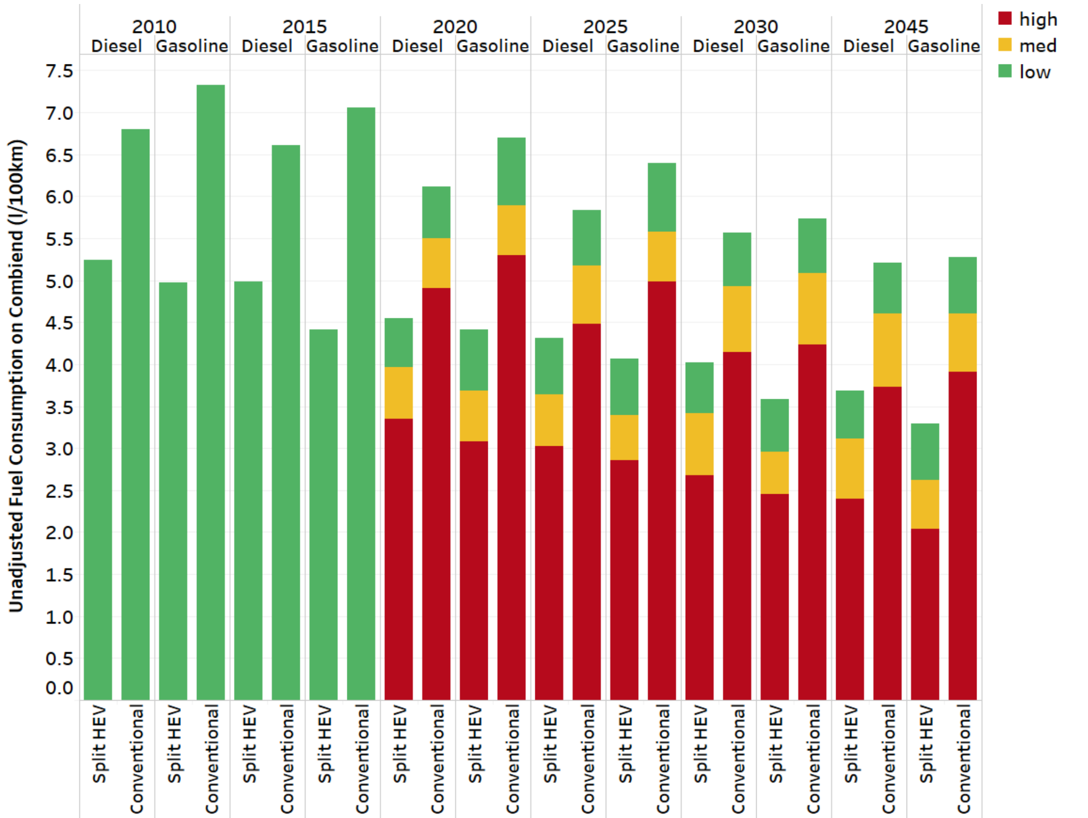

FIGURE 8.10 Conventional and split HEV unadjusted fuel consumption on combined driving cycle

This comparison can be further evolved in terms of fuel consumption ratios between the power-split HEV and conventional vehicles as shown in Figure 8.11. The labels high, medium, and low refer to the different technology performance cases.

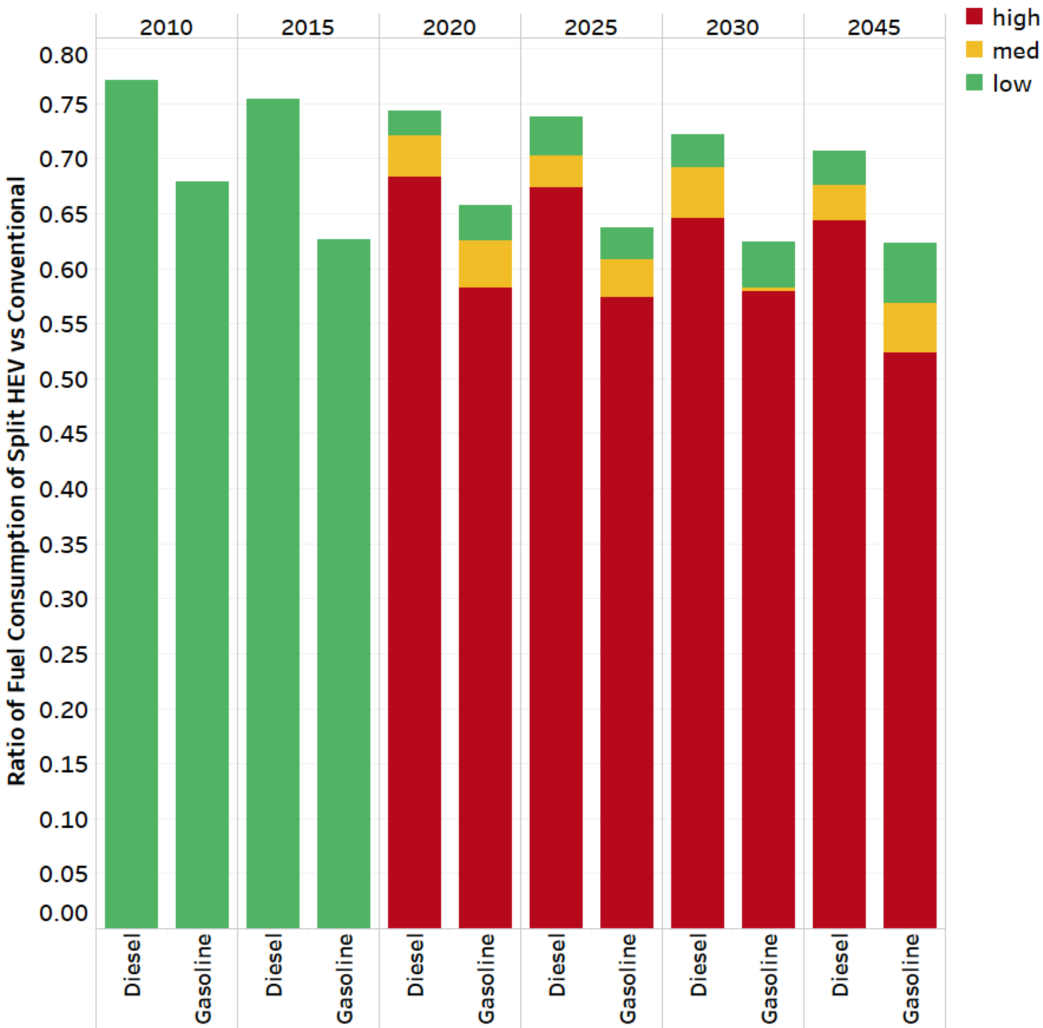

FIGURE 8.11 Ratio of fuel consumption of split HEV vs. Conventional

The figure shows the ratio follows a slowly decreasing trend line. The power-split midsize vehicle consumes between 24% and 40% less fuel compared to conventional vehicles until 2015, and the drop ranges to about 50% in 2045.

8.2.2 Power Split HEV vs. Fuel-Cell HEV

Figure 8.12 illustrates the evolution of fuel-cell HEVs compared to power-split HEVs (gasoline fuel) for midsize vehicle class in terms of fuel consumption.

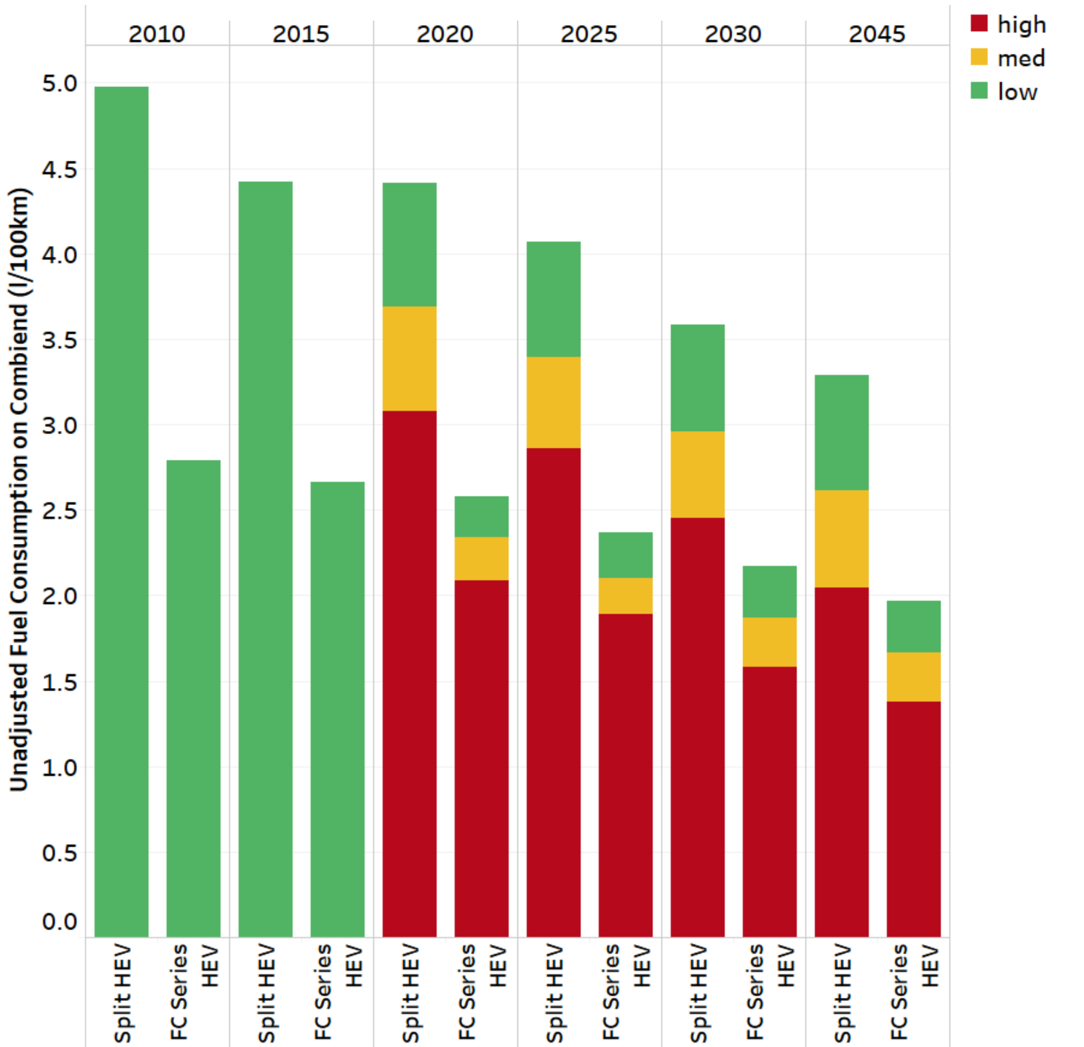

FIGURE 8.12 Power-split HEV (gasoline) vs fuel-cell HEV fuel consumption

The ratios of fuel consumption of fuel-cell HEVs compared to power-split HEVs (gasoline fuel) are shown in Figure 8.13.

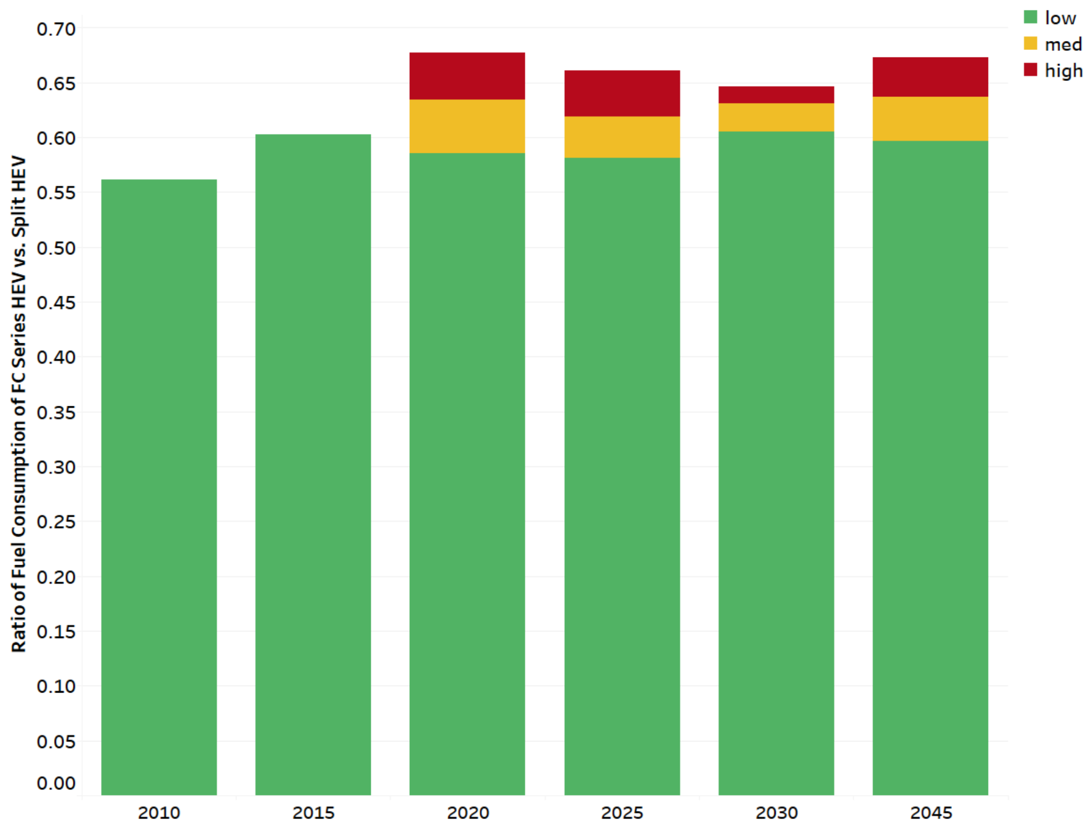

FIGURE 8.13 Ratio of fuel consumption by fuel-cell HEV vs. power-split HEV

It can be observed that the fuel cell vehicles consistently consume less fuel, and the ratios vary over time and across the different uncertainty cases. This evolving trend helps to study and compare the evolution of each of the powertrains. In the reference 2010 lab year, the fuel cell consumes about 45% less fuel compared to the power-split HEV. However, this difference drops significantly to around 35% in year 2045 (for the high technology progress case). This reduction shows a greater evolution in power-split HEV technologies when compared to fuel-cell vehicle technologies; hence, the difference in benefits observed over time.

8.3 EVOLUTION OF HYDROGEN-FUELED VEHICLES

8.3.1 Fuel-Cell HEV vs. Conventional Engines

The evolution of fuel-cell HEVs compared to conventional gasoline vehicles of midsize vehicle class can be observed in Figure 8.14.

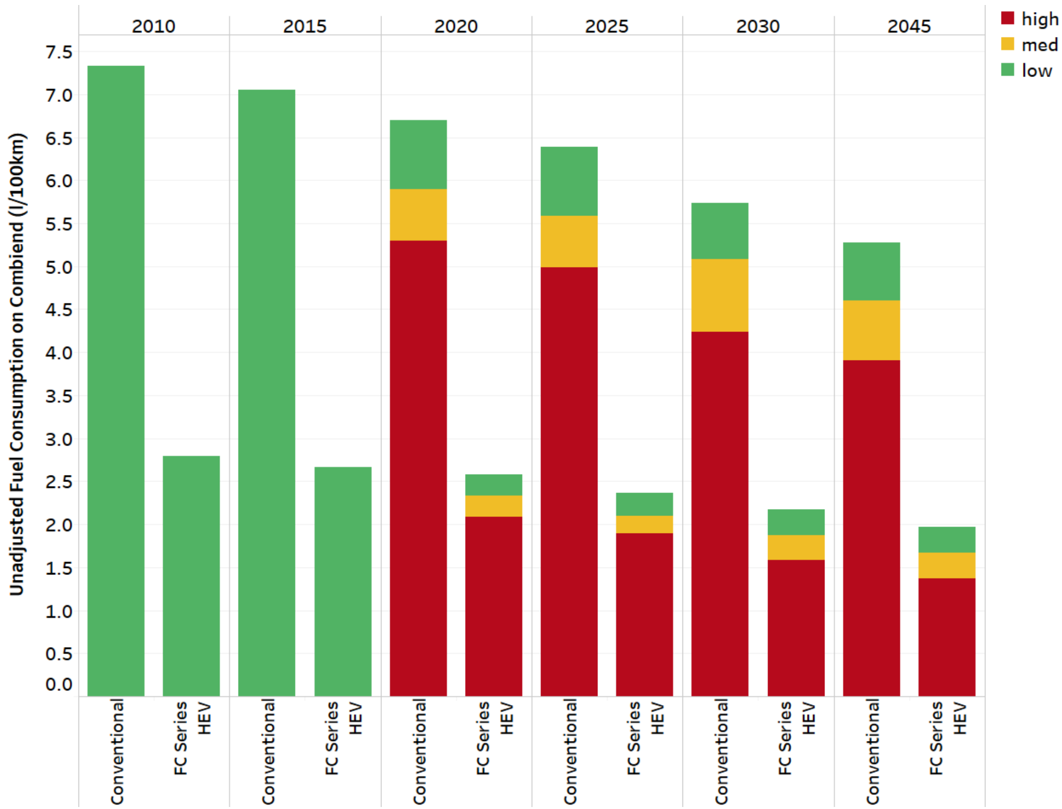

FIGURE 8.14 Conventional gasoline and. fuel-cell HEV unadjusted fuel consumption

The ratio of fuel consumption of the fuel-cell HEV compared to the conventional gasoline midsize vehicle is further illustrated in Figure 8.15.

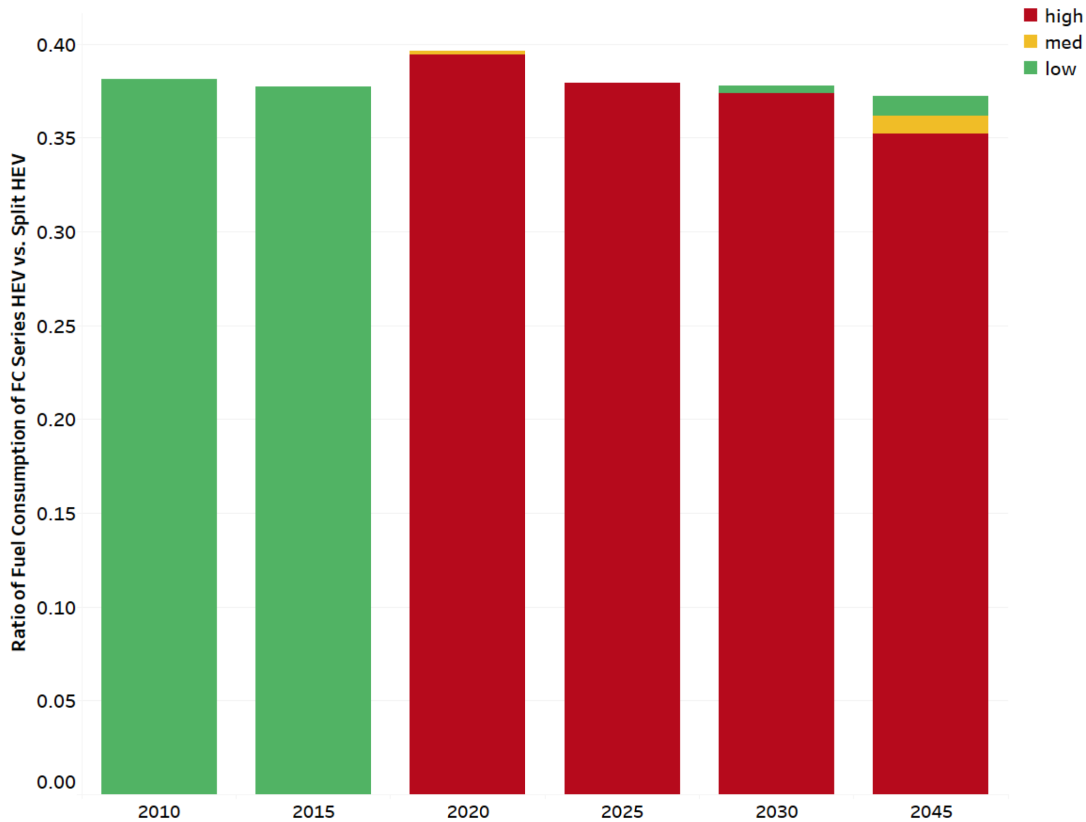

FIGURE 8.15 Conventional gasoline vs. fuel-cell HEV fuel consumption

The figure shows the effects of technology improvements in the evolution of conventional vehicles. In reference 2010 lab year, the fuel-cell HEVs consume about 55% less fuel compared to conventional gasoline vehicles. However, this improvement increases to about 65% for the high case in lab year 2045. This increase in improvement shows that fuel-cell HEVs respond to a much more aggressive advance in technologies, resulting in reduced fuel consumption.

8.4 EVOLUTION OF BATTERY ELECTRIC VEHICLES

8.4.1 BEV vs. Conventional Engines

The evolution of BEVs of different AERs compared to conventional gasoline vehicles of midsize vehicle class in terms of gasoline-equivalent fuel consumption can be observed in Figure 8.16.

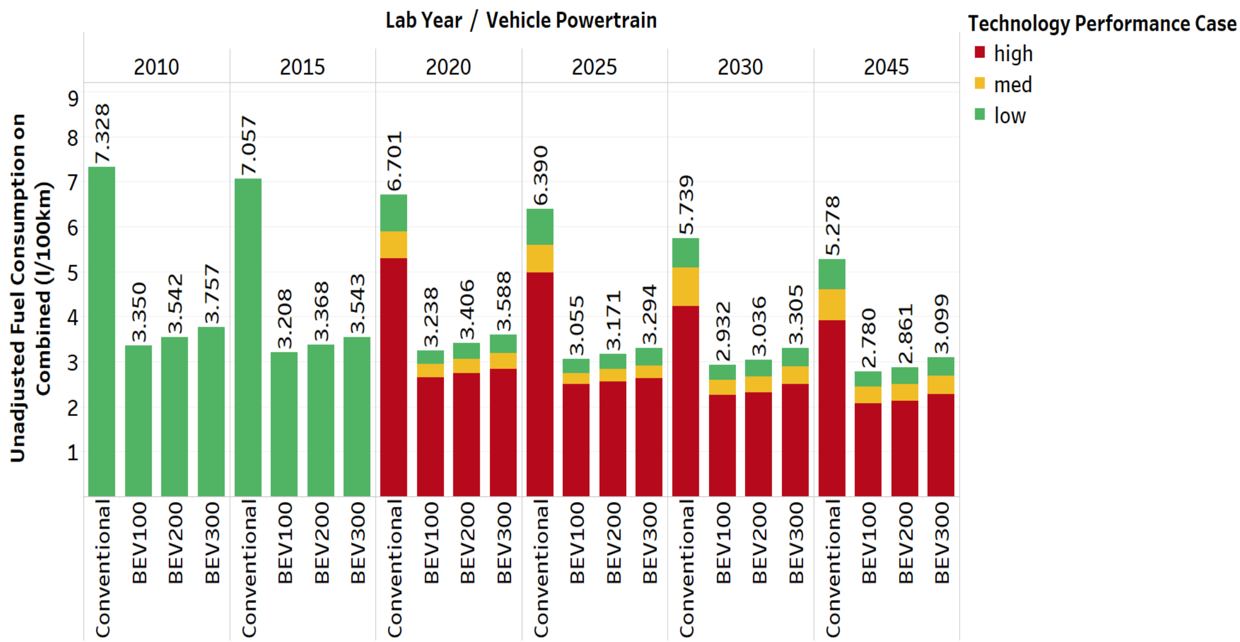

FIGURE 8.16 Conventional gasoline vehicles vs. BEVs gasoline-equivalent fuel consumption

It can be observed that for BEV100, the improvement in fuel consumption over conventional reduces from 54% in 2010 to about 47% in 2045. For BEV200, the improvement in fuel consumption over conventional reduces from 52% to about 46% in 2045 and for BEV300, the improvement in fuel consumption over conventional reduces from 49% in 2010 to about 42% in 2045. This shows that the evolution of conventional vehicles is much more aggressive when compared to battery electric vehicles and leads to a much more aggressive reduction in fuel consumption when compared to the battery electric vehicles.

9 VEHICLE MANUFACTURING COSTS

In addition to the three levels of technology performance uncertainties, the study computes three levels of technology cost uncertainties (low, medium, and high). To simplify, the technology performance/technology cost uncertainty levels are illustrated according to technology progress cases low (low technology performance/high technology cost uncertainty), medium (medium technology performance/ medium technology cost uncertainty), and high (high technology performance/low technology cost uncertainty). All costs reported in this section are in USD (2015). The cost values in this section represent manufacturing costs, and not sales prices.

9.1 EVOLUTION OF SPECIFIC POWERTRAIN CONFIGURATIONS

9.1.1 Conventional

Figure 9.1 illustrates the manufacturing costs for conventional midsize vehicles. The labels high, medium, and low represent the different technology progress uncertainty cases. As can be observed from the illustration, vehicle prices increase from lab year 2010 to 2045. The increase in costs can be explained by several factors including lightweighting—the decrease in vehicle weight is accompanied by an increase in material cost brought about by escalating use of aluminum or carbon fiber and advanced component technologies.

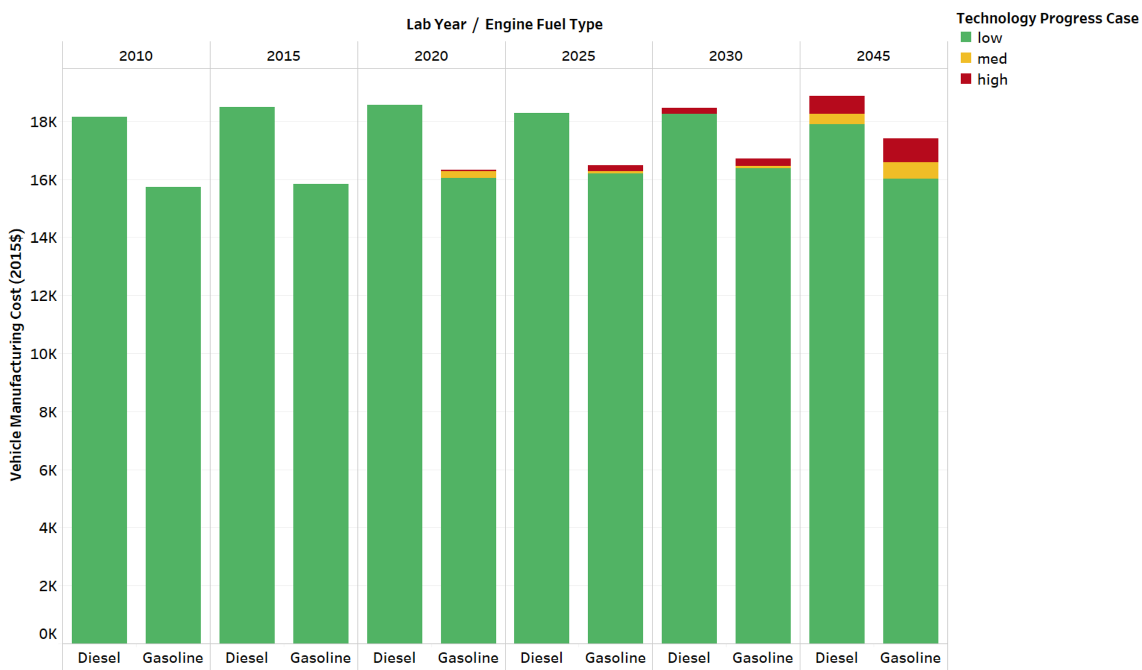

FIGURE 9.1 Manufacturing cost of conventional vehicles

The difference in manufacturing cost between the diesel and gasoline vehicles can be explained by the differences in engine cost—diesel engine costs are much higher than gasoline vehicle engine costs, driving the difference in manufacturing costs.

9.1.2 Split HEV

Figure 9.2 shows the vehicle manufacturing costs for the power-split HEVs. The labels low, medium, and high represent the different technology progress cases.

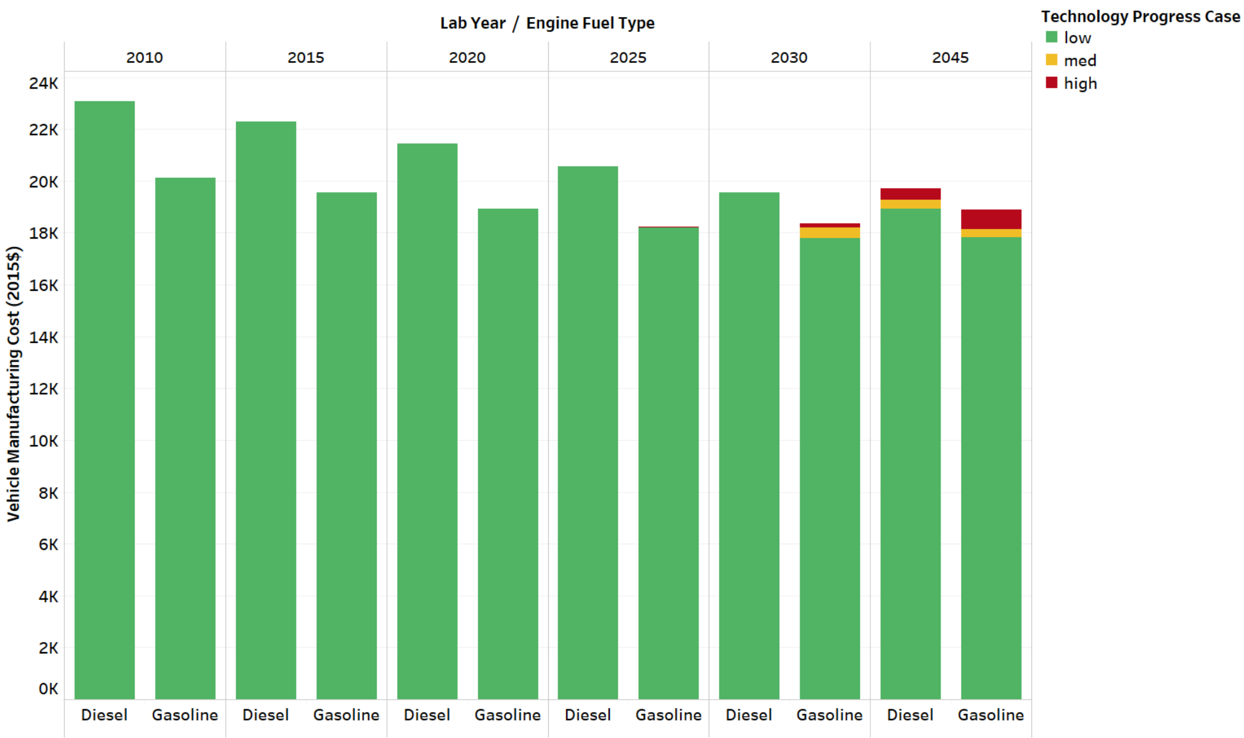

FIGURE 9.2 Manufacturing cost of midsize Power-split HEV vehicles

Over time, manufacturing costs decrease for power-split HEVs because energy storage and electric machine costs decrease in the future. Although the glider cost increases over time, the overall effect on the manufacturing cost follows a downward trend. Similar to the explanation in the trend observed for conventional vehicles, it can be observed that the gasoline power-split HEVs are cheaper than the corresponding diesel HEVs.

9.1.3 PHEVs

Figure 9.3 below illustrates the vehicle manufacturing cost evolution for the PHEV vehicles with different AERs. The labels low, medium, and high represent the different technology progress cases.

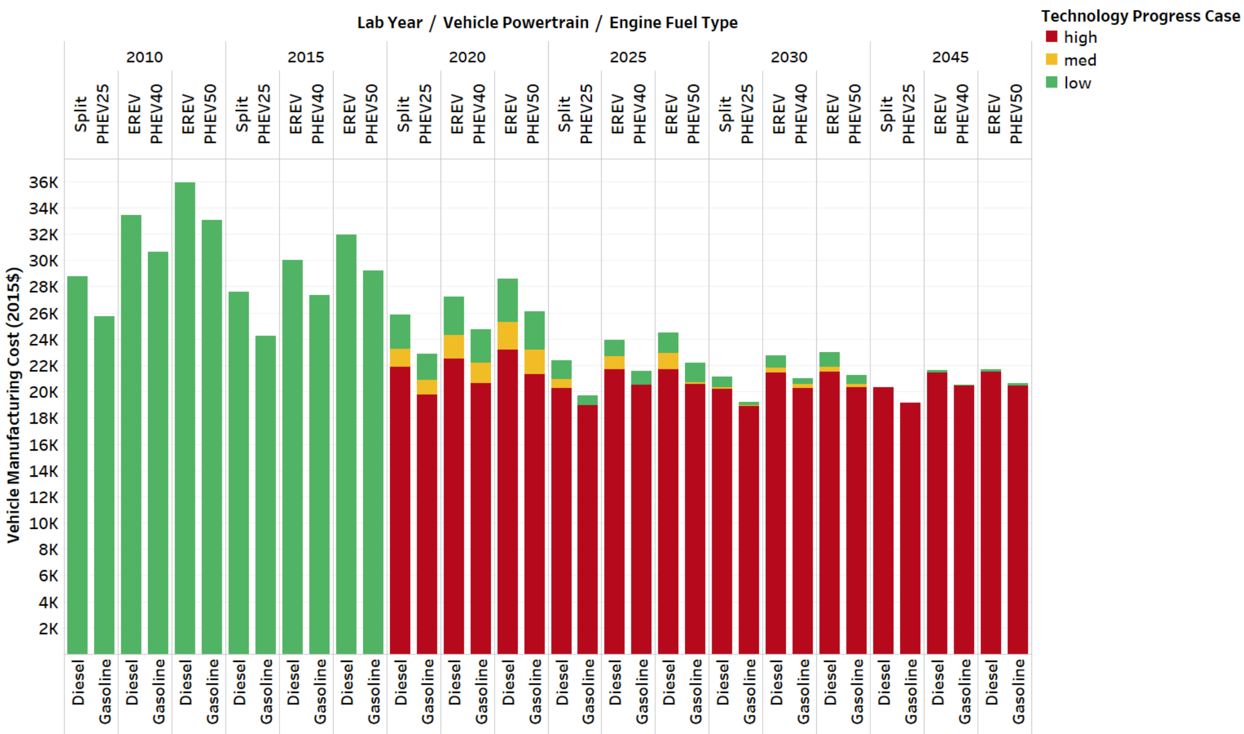

FIGURE 9.3 Manufacturing cost of midsize PHEV vehicles

The overall costs follow similar trends across the different fuels. Within each case, increasing AER increases the manufacturing cost owing to bigger batteries. However, with time the battery cost decreases, resulting in vehicle manufacturing cost decreases. This effect is further fueled by future battery sizes, as can be observed by the differences across different AERs. It can be further observed that by the year 2045, the uncertainty in technology progress converges which can be explained by the compression in the variation of cost uncertainties for different vehicle components by the year 2045.

9.1.4 Fuel-Cell Vehicles

Manufacturing costs of fuel-cell vehicles follow similar trends, as shown in Figure 9.4.

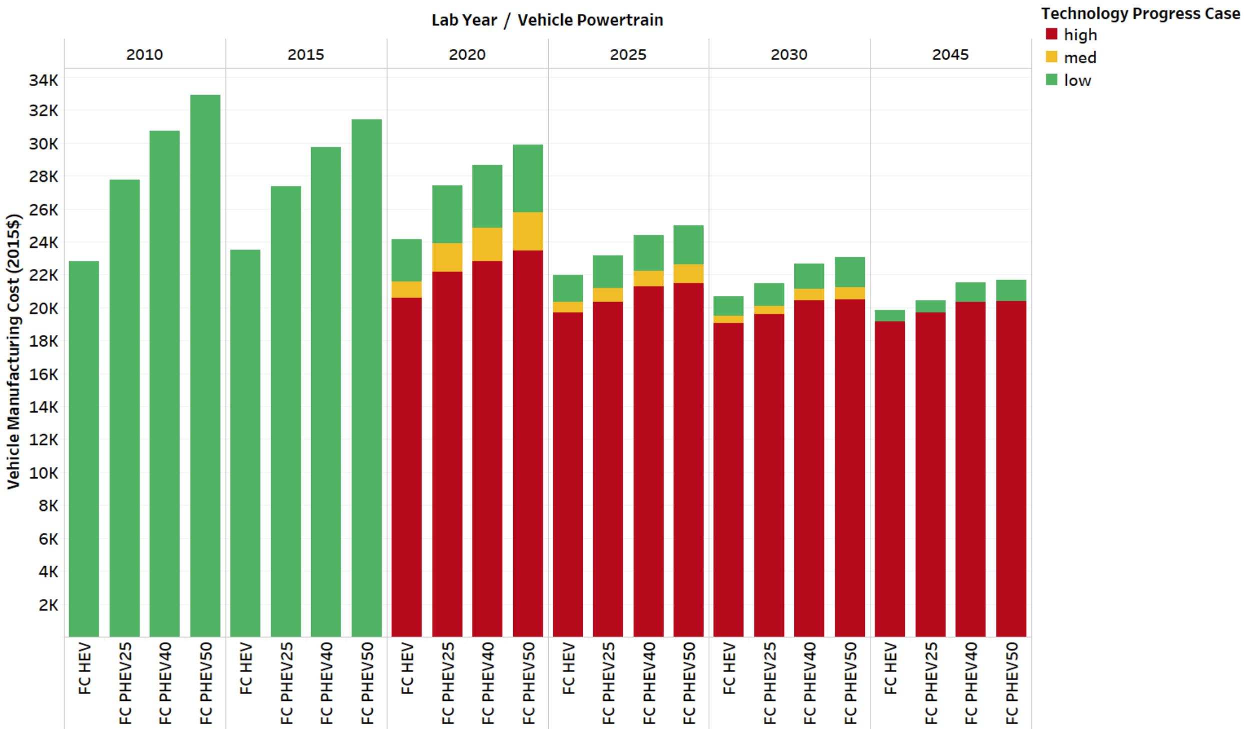

FIGURE 9.4 Manufacturing cost of midsize fuel-cell vehicles

It can be seen that with time the difference in manufacturing costs between the different powertrains decreases. For example, in lab year 2010, a fuel-cell PHEV50 is almost 50% more expensive to manufacture than a fuel-cell HEV. This difference drops to about 9% in lab year 2045.

9.1.5 Electric Vehicles

Figure 9.5 illustrates the evolution of electric vehicles in terms of manufacturing cost.

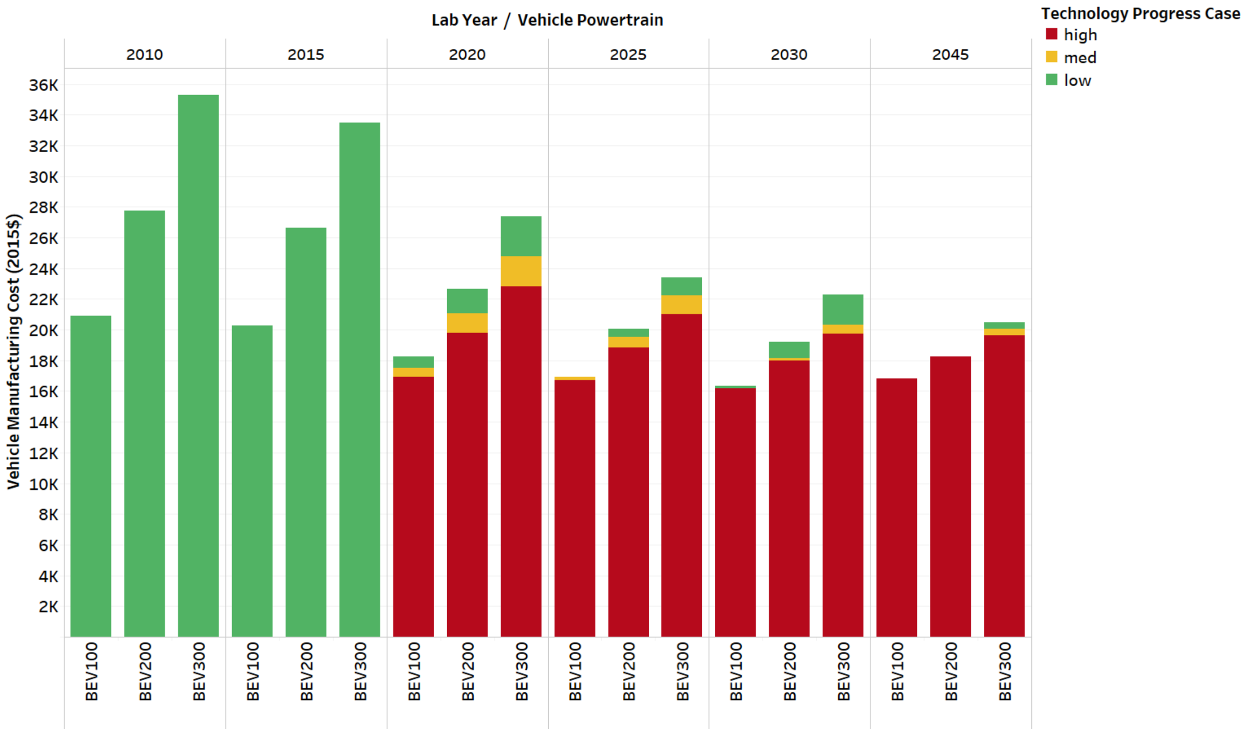

FIGURE 9.5 Manufacturing cost of midsize BEVs

Lightweighting has an effect on battery sizes, and hence decreases the battery costs in future years. Battery size in turn affects the major manufacturing cost of the battery electric vehicles. It can be seen that higher range BEVs have a greater impact on the manufacturing costs in future years.

10 VEHICLE FUEL CONSUMPTION VS. VEHICLE MANUFACTURING COSTS

This section discusses the evolution of fuel consumption with respect to vehicle manufacturing costs for the low, medium, and high technology progress cases discussed in Section 9.

10.1 CONVENTIONAL VEHICLES

Figure 10.1 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for conventional vehicles across multiple vehicle classes. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different vehicle classes.

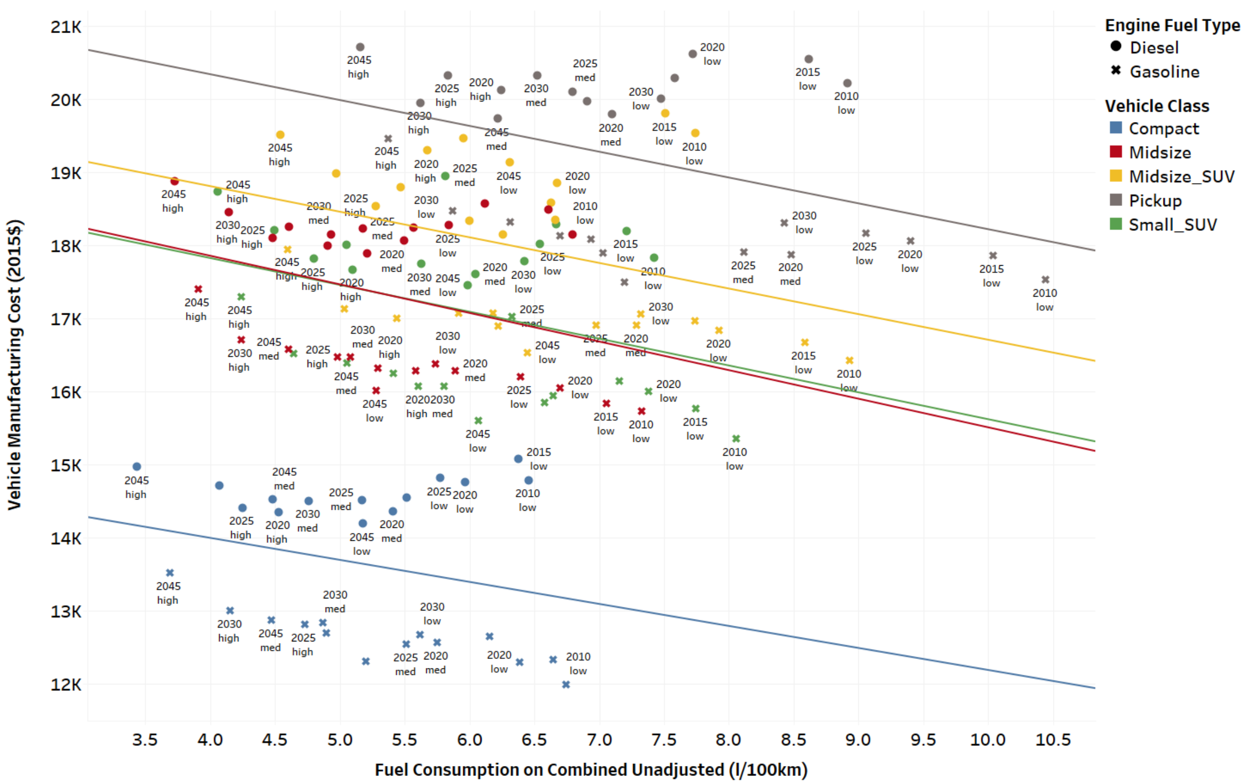

FIGURE 10.1 Vehicle manufacturing cost vs. fuel consumption for conventional vehicles

One key observation is diesel vehicles have relatively higher manufacturing costs compared to gasoline vehicles. In addition, the figure shows the relative position of the different vehicle classes in terms of fuel consumption and manufacturing costs: midsize vehicles, small SUVs, and midsize SUVs cluster closely to each other, while compact and pickup classes lie on the two extremes. The trend line in the plot also confirms this observation.

10.2 SPLIT HEVS

Figure 10.2 shows the comparison of vehicle manufacturing cost vs. fuel consumption for split HEVs across multiple vehicle classes. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different vehicle classes.

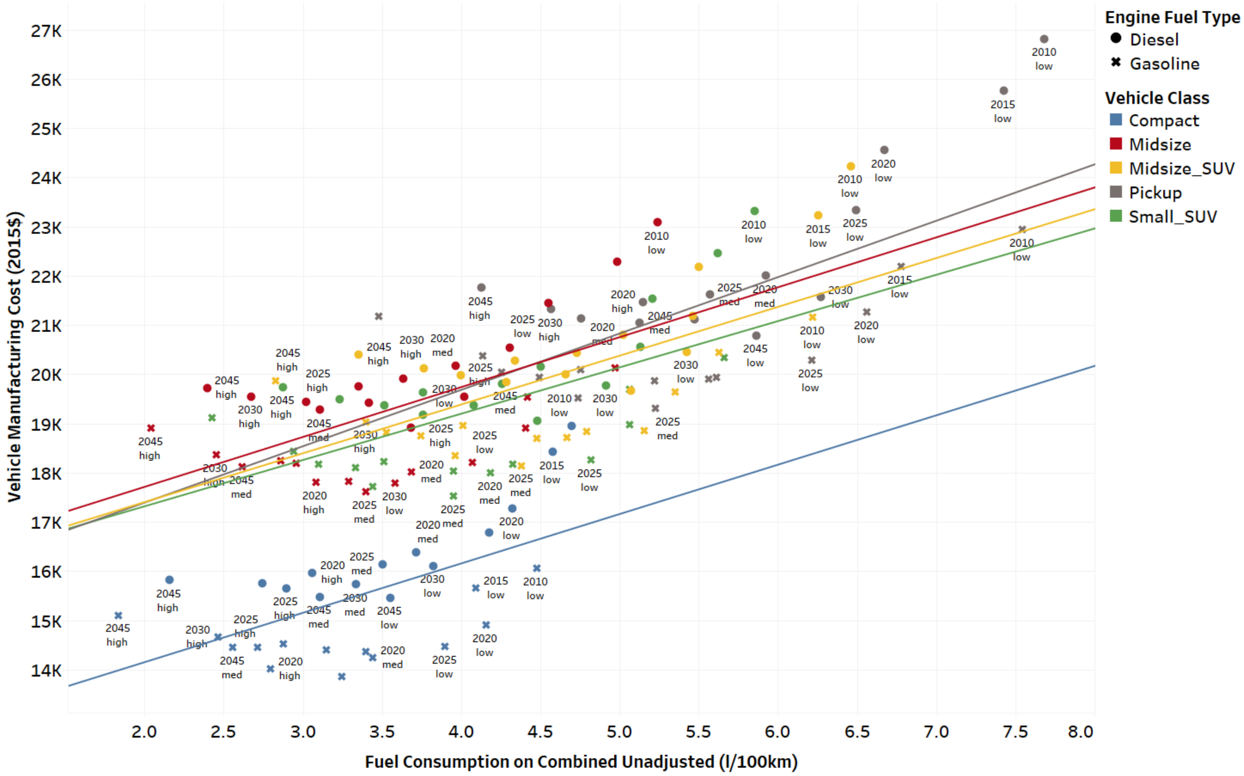

FIGURE 10.2 Vehicle manufacturing cost vs. fuel consumption for split-HEVs

As observed earlier, diesel vehicles tend to be more expensive compared to gasoline vehicles. The effect of the different vehicle classes on fuel consumption and manufacturing cost is similar to that observed earlier. The plot further shows how the fuel consumption and manufacturing costs progress across the different lab years. From the trend lines, it can be observed that over time, both fuel consumption and manufacturing costs decrease. As discussed earlier, these decreases come from the drop in battery and electric machine costs, which play a dominant role in manufacturing cost. The trend line also confirms the clustering.

10.3 SPLIT/E-REV PHEVS

Figure 10.3 below shows the comparison of vehicle manufacturing cost vs. fuel consumption for PHEVs across multiple vehicle classes for both diesel and gasoline vehicles. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different AERs.

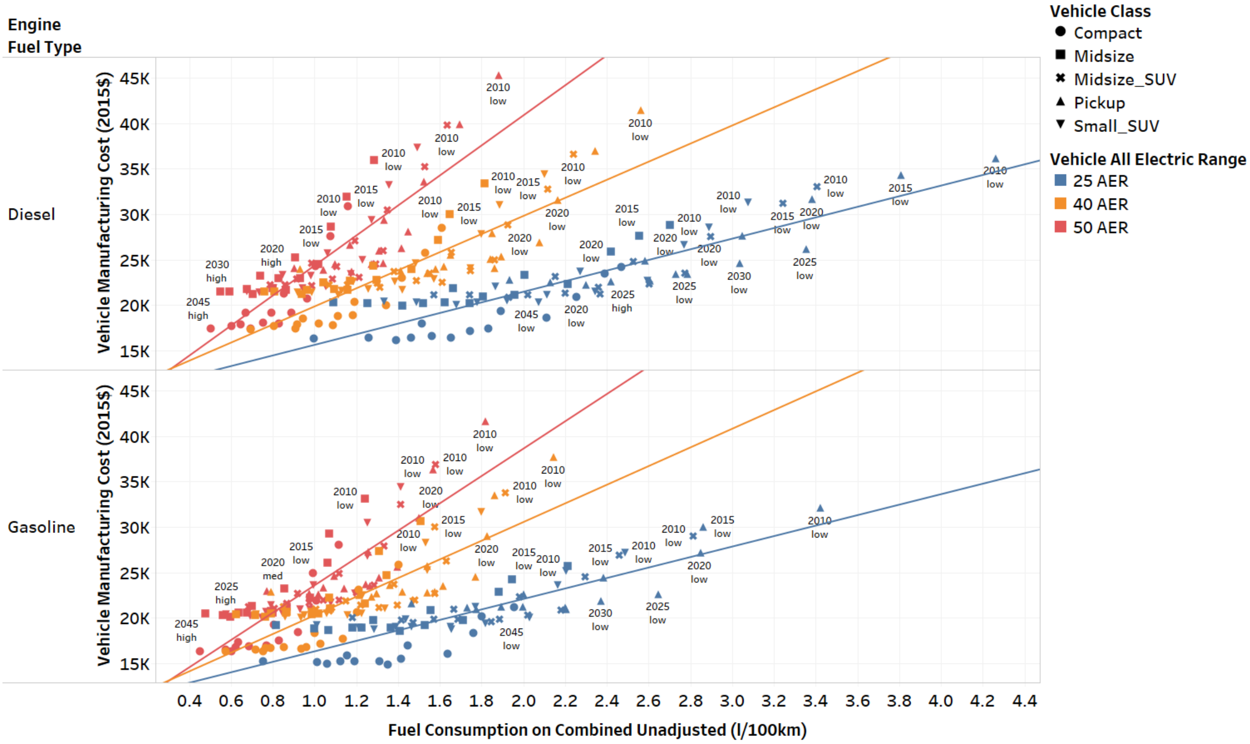

FIGURE 10.3 Vehicle manufacturing cost vs. fuel consumption for PHEVs

The different vehicle classes follow trends similar to those previously discussed. It can be observed that as AER increases, manufacturing cost increases (owing to bigger battery sizes) and fuel consumption decreases. The effect of technological improvements over the years can be seen through a reduction in fuel consumption and manufacturing cost from lab year 2010 to 2045. Furthermore, the trend lines show an aggressive fall in manufacturing costs with respect to improved fuel consumption for PHEVs with higher AERs. This cost decrease can be explained by the improvement in component specifications followed by the decrease in battery costs over time.

10.4 FUEL-CELL HEVS

Figure 10.4 compares vehicle manufacturing cost and fuel consumption for fuel-cell HEVs across multiple vehicle classes. The different colored lines represent the trend lines of vehicle manufacturing cost vs. fuel consumption for different vehicle classes.

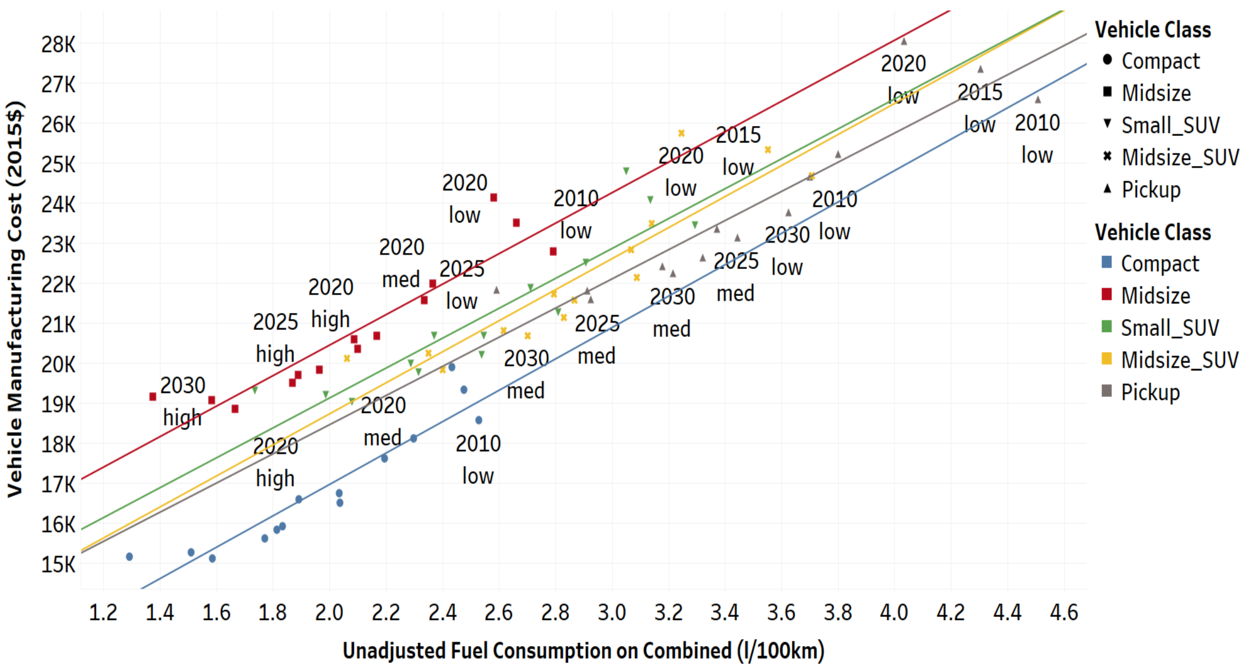

FIGURE 10.4 Vehicle manufacturing cost vs. fuel consumption for fuel-cell HEVs

The trends for fuel cell HEVs are similar to those previously observed for split HEV vehicles.

10.5 FUEL-CELL PHEVS

Figure 10.5 illustrates the comparison of vehicle manufacturing cost vs. fuel consumption for fuel-cell PHEVs across multiple vehicle classes.

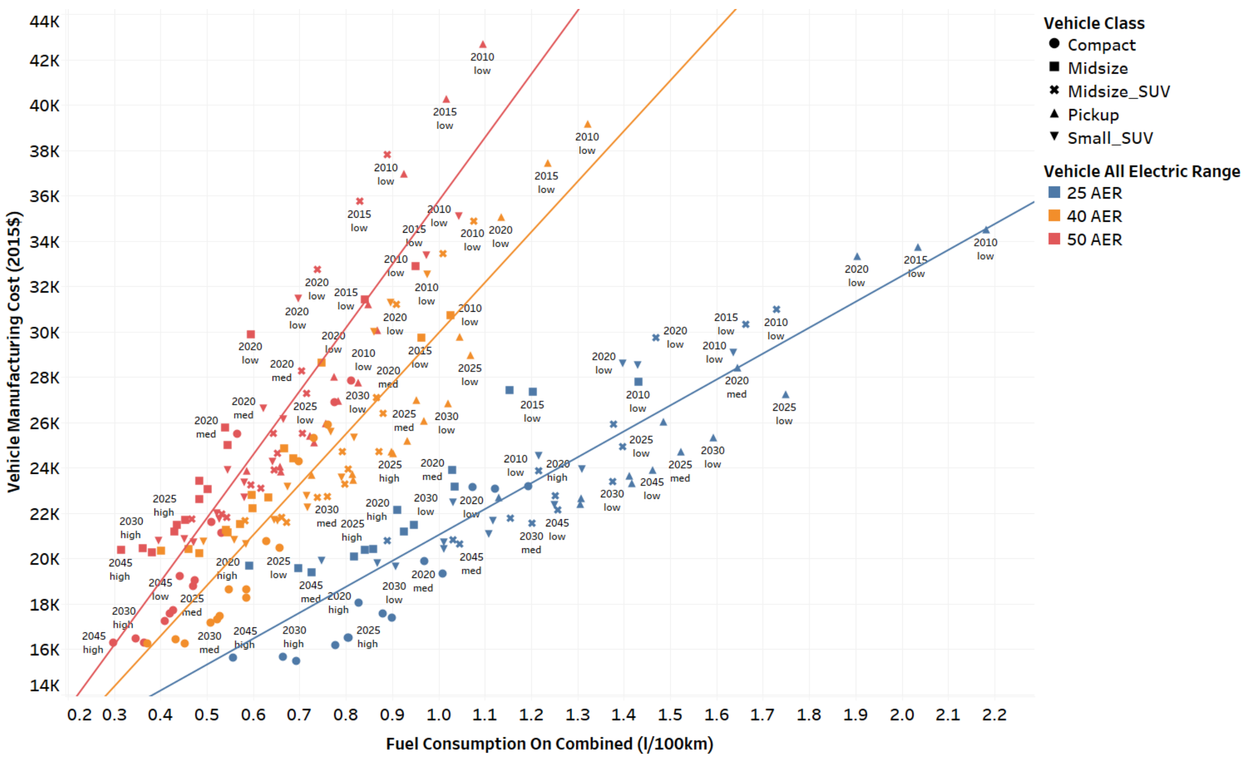

FIGURE 10.5 Vehicle manufacturing cost vs. fuel consumption for fuel-cell PHEVs

Fuel-cell PHEVs follow the same trends as split/E-REV PHEV vehicles. As AER increases, the vehicle manufacturing cost increases (owing to bigger batteries) and fuel consumption decreases. The different vehicle classes follow the same trend in terms of manufacturing costs and fuel consumption.

11 CONCLUSION

Technology improvements lead to significant reductions in energy consumption and cost across light-duty vehicle applications. Because of uncertainty in the evolution of technologies, different areas of development reflect variations in potential improvements.

Over the next decade, advanced technologies are anticipated to impact the vehicle energy consumption. In the short term, both HEVs and PHEVs allow significant fuel displacement—with additional costs. In the long term, fuel-cell vehicles and BEVs demonstrate very high fuel displacement potential.

11.1 VEHICLE POWERTRAIN SIZING

Vehicle weight is expected to decrease between 10% and 48% by 2045 across powertrain configurations. The weight reduction, however, varies with the configuration. For the configurations using an engine, the weight reduction for the gasoline conventional powertrain ranges between 12% and 28%, power-split HEVs between 12% and 31%, low-energy PHEVs (with all-electric ranges [AERs] of 25 miles) between 17% and 37%, and high-energy PHEVs (AERs of 40 and 50 miles) between 20% and 41%. Configurations with fuel-cell systems demonstrate a larger weight reduction, with fuel-cell HEV weight reductions ranging between 15% and 38%, low-energy PHEV25s (i.e., AERs of 25 miles) between 19% and 41%, and high-energy PHEV40s and PHEV50s (AERs of 40 and 50 miles) between 19% and 44%. Finally, battery-powered electric vehicles (BEVs) achieve a weight reduction ranging between 18% and 48%. Overall, significant weight reductions can be achieved compared with current technologies, especially for vehicles with large batteries.

Because of lightweighting and component efficiency improvements, the peak power of engine and fuel-cell systems could be significantly reduced over time to meet current vehicle technology specifications (VTS). Engine peak power could be reduced by 2045 over a 7% to 39% range for conventional gasoline, 14% to 32% for gasoline power-split HEVs, and 18% to 37% for low-energy and high-energy PHEVs. Hydrogen-fueled vehicles demonstrate a similar peak-power improvement over time, with fuel-cell system power decreasing in the range of 14% to 38% for HEVs, and about 18% to 37% for low and high-energy PHEVs.

Because of the impact of the component max-torque curves, maintaining a constant power-to-weight (P/W) ratio between all configurations leads to an inconsistent comparison between technologies due to different performances. While performance (i.e., lapsed time for 0–60 mph) is the primary factor used to size components for current technologies, aggressive future lightweighting can make gradeability requirements one of the critical sizing criteria. Most of the component peak powers show a strong linear correlation with vehicle weight. As a result, it is necessary to include secondary effects when analyzing the lightweighting benefits.

Battery peak power is expected to decrease over time to meet current vehicle performance. Battery power is expected to decrease up to 50% for gasoline-engine HEVs and PHEVs. Battery total energy will decrease significantly owing to other component improvements, as well as a wider usable state of charge (SOC) range. The reduction in energy required for PHEVs and BEVs could range from 24% to 55% by 2045.

While fuel selection influences the engine size for conventional vehicles (i.e., diesel has lower peak power than gasoline due to higher maximum torque at low speed), the power required to meet the VTS for EDVs is comparable across all fuels.

11.2 POWERTRAIN COMPARISONS

A comparison of powertrain configurations shows the following:

- Conventional gasoline vehicles vs. engine HEVs:

  - For midsize power split HEVs, the fuel consumption reduction due to hybridization increases over time from 32% in 2010 to between 38% and 48% in 2045. The fuel consumption reduction is compared to a midsize conventional gasoline vehicle in 2010 lab year.

  - For gasoline HEVs in 2045, the fuel consumption reduction ranges from 39% to 49% for compact cars, 38% to 48% for midsize cars, 35% to 43% for small SUVs, 30% to 38% for midsize SUVs, and 27% to 35% for pickup trucks. The fuel consumption reduction is compared to conventional gasoline vehicles in 2010 lab year for the respective vehicle classes.

- Conventional gasoline vehicles vs. engine PHEVs:

  - For PHEV25s, the reduction in fuel consumption compared to conventional gasoline vehicles improves over time from 70% in 2010 to between 74% and 79% in 2045 for the respective years.

  - For PHEV40s, the reduction in fuel consumption follows a similar trend and improves from 79% in 2010 to between 80% and 84% in 2045.

  - For PHEV50s, the reduction in fuel consumption improves over time from 83% in 2010 to between about 85% and 88% in 2045.

  - The percent improvement decreases for higher weight classes.

- Conventional gasoline vehicles vs. fuel-cell HEVs:

  - For fuel-cell HEVs, the reduction in fuel consumption compared to conventional gasoline vehicles increases over time across the different vehicle classes.

- For compacts, the reduction in fuel consumption for fuel-cell HEVs compared to gasoline conventional vehicles increases from 63% in 2010 to about 65% in 2045, for the respective years.

- For midsize vehicles, the reduction in fuel consumption for fuel-cell HEVs compared to gasoline conventional vehicles increases from 62% in 2010 to between about 63% and 65% in 2045, for the respective years.

- For small SUVs, the percent reduction in fuel consumption for fuel-cell HEVs compared to gasoline conventional vehicles increases from 30% in 2010 to between about 35% and 43% in 2045, for the respective years.

- For midsize SUVs, the percent reduction in fuel consumption for fuel-cell HEVs compared to gasoline conventional vehicles increases from 31% in 2010 to between about 31% and 38% in 2045, for the respective years.

- For pickups, the percent reduction in fuel consumption for fuel-cell HEVs compared to gasoline conventional vehicles increases from 27% in 2010 to between 28% and 35% in 2045, for the respective years.

- Engine HEVs vs. fuel-cell HEVs:

  - Fuel cell system technology offers consistently lower fuel consumption than power-split HEV technologies.

  - For compact cars, the fuel consumption improvement of power-split HEVs compared to fuel-cell HEVs in 2010 is about 44%, which decreases to between 30% and 42% in 2045. For midsize cars, the fuel consumption improvement in 2010 is about 44%, and decreases to between about 32% and 40% in 2045. For small SUVs, the fuel consumption improvement drops from 42% in 2010 to between about 28% and 36% in 2045. The reduction in fuel consumption decreases from 40% in 2010 to between about 27% and 37% in 2045. For pickups, the improvement in fuel consumption decreases from 40% in 2010 to between about 25% and 36% in 2045.

11.3 EVOLUTION OF FUEL COMPARISONS

Comparisons of gasoline and diesel fuel show the following:

- For conventional diesel vehicles, the gasoline-equivalent fuel consumption improvement compared to gasoline vehicles will tend to decrease in the future. For conventional vehicles, the fuel consumption advantage of diesel engines drops from 7% in 2010 to between 4% and 5% in 2045.

- For power-split HEVs, the diesel vehicles observe a negative improvement when compared to gasoline vehicles. In 2010, diesel-powered HEVs consume 5% more fuel, which increases to between about 12% and 17% in 2045.

- For PHEVs, a similar trend is observed to that of power-split HEVs.

11.4 COST EVOLUTION COMPARED WITH REFERENCE 2010 LAB YEAR GASOLINE CONVENTIONAL VEHICLES

Table 11-1 shows the additional manufacturing costs by 2045 compared with the reference 2010 gasoline conventional vehicle. The table shows a considerable uncertainty range for the additional manufacturing costs across all technologies. This high uncertainty highlights the need to pursue aggressive research over the next decade to bring the cost of advanced technologies to a level that will favor high market penetrations.

TABLE 11-1 Additional manufacturing costs in USD (2015) of each powertrain type by 2045 lab year, compared with reference 2010 lab year gasoline conventional engine for midsize class

Fuel/ Powertrain	Conven-tional	Power-split HEV	PHEV25	PHEV40	PHEV50	BEV100	BEV200	BEV300
Gasoline	300–1700	2100–3200	3200–3500	4400–4800	4400–4900			
Diesel	2200–3200	3200–4000	4200–4600	5500–5900	5500–5900			
Fuel Cell		3100–4000	3700–4700	4500–5800	4600–6000			
BEV						980–2000	2300–3500	4300–5100

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APPENDIX

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
BEV100 DM	2010	low	high	Compact		20611.2	1528.0			185.9	203.4			17026.7
BEV100 DM	2010	low	high	Midsize		22117.5	1781.0			205.3	218.7			21071.1
BEV100 DM	2010	low	high	Midsize_SUV		31070.9	2025.0			257.8	306.4			23892.1
BEV100 DM	2010	low	high	Pickup		38357.9	2346.0			310.1	378.8			26649.2
BEV100 DM	2010	low	high	Small_SUV		27166.4	1948.0			234.1	266.3			22188.8
BEV100 DM	2015	low	high	Compact		20025.4	1507.0			179.5	198.8			16672.3
BEV100 DM	2015	low	high	Midsize		21183.4	1686.0			193.1	210.0			20550.0
BEV100 DM	2015	low	high	Midsize_SUV		29884.5	1918.0			243.1	295.1			23204.5
BEV100 DM	2015	low	high	Pickup		37155.9	2215.0			292.0	364.7			25938.8
BEV100 DM	2015	low	high	Small_SUV		26047.8	1838.0			220.3	256.4			21595.5
BEV100 DM	2020	low	high	Compact		21185.2	1428.0			182.5	208.1			14886.5
BEV100 DM	2020	low	high	Midsize		21666.8	1588.0			193.7	214.8			18638.9
BEV100 DM	2020	low	high	Midsize_SUV		28475.2	1798.0			233.0	280.9			20112.2
BEV100 DM	2020	low	high	Pickup		36622.9	2085.0			283.8	360.3			22361.3
BEV100 DM	2020	low	high	Small_SUV		26687.1	1732.0			221.5	263.1			19264.3
BEV100 DM	2025	low	high	Compact		20714.9	1380.0			176.5	203.5			13746.0
BEV100 DM	2025	low	high	Midsize		20431.6	1534.0			183.5	202.2			17256.3
BEV100 DM	2025	low	high	Midsize_SUV		28753.7	1738.0			229.0	284.7			18662.0
BEV100 DM	2025	low	high	Pickup		35808.4	2005.0			273.1	351.7			20411.7
BEV100 DM	2025	low	high	Small_SUV		26527.8	1672.0			215.5	261.7			17826.6
BEV100 DM	2030	low	high	Compact		18904.1	1353.0			169.4	187.0			13126.6
BEV100 DM	2030	low	high	Midsize		19306.5	1507.0			178.7	191.1			16727.8
BEV100 DM	2030	low	high	Midsize_SUV		29236.8	1714.0			232.4	291.0			18303.4

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
BEV100 DM	2030	low	high	Pickup		34957.6	1971.0			269.0	344.9			19817.0
BEV100 DM	2030	low	high	Small_SUV		25840.1	1645.0			211.9	255.9			17317.9
BEV100 DM	2045	low	high	Compact		18175.1	1306.0			162.6	180.4			12539.5
BEV100 DM	2045	low	high	Midsize		18312.8	1453.0			169.8	180.8			16121.6
BEV100 DM	2045	low	high	Midsize_SUV		28250.5	1650.0			223.7	281.0			17503.3
BEV100 DM	2045	low	high	Pickup		33639.4	1894.0			258.4	332.9			18892.9
BEV100 DM	2045	low	high	Small_SUV		24240.2	1582.0			199.7	239.7			16509.7
BEV200 DM	2010	low	high	Compact		42518.7	1682.0			198.1	212.2			23209.8
BEV200 DM	2010	low	high	Midsize		46011.3	1948.0			218.7	227.9			27812.9
BEV200 DM	2010	low	high	Midsize_SUV		64460.5	2260.0			277.1	321.2			33317.9
BEV200 DM	2010	low	high	Pickup		79856.8	2637.0			335.0	398.1			38360.1
BEV200 DM	2010	low	high	Small_SUV		55513.8	2147.0			249.7	277.6			30185.6
BEV200 DM	2015	low	high	Compact		41294.1	1642.0			189.8	206.2			22598.7
BEV200 DM	2015	low	high	Midsize		43788.2	1829.0			204.1	217.8			26849.4
BEV200 DM	2015	low	high	Midsize_SUV		61640.6	2120.0			259.2	307.8			32051.3
BEV200 DM	2015	low	high	Pickup		76230.5	2461.0			312.3	381.2			36819.0
BEV200 DM	2015	low	high	Small_SUV		53690.0	2012.0			233.6	266.3			29282.0
BEV200 DM	2020	low	high	Compact		43075.8	1564.0			193.2	216.2			18964.8
BEV200 DM	2020	low	high	Midsize		44684.9	1732.0			205.3	223.4			22930.2
BEV200 DM	2020	low	high	Midsize_SUV		58688.7	1986.0			247.8	292.5			25745.9
BEV200 DM	2020	low	high	Pickup		75804.0	2329.0			303.4	376.0			29651.7
BEV200 DM	2020	low	high	Small_SUV		55043.7	1908.0			235.2	273.8			24542.5
BEV200 DM	2025	low	high	Compact		42279.3	1479.0			184.3	209.9			16927.4
BEV200 DM	2025	low	high	Midsize		41736.6	1631.0			191.4	208.2			20400.5
BEV200 DM	2025	low	high	Midsize_SUV		58741.2	1875.0			239.7	293.9			23086.7

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
BEV200 DM	2025	low	high	Pickup		73118.5	2176.0			286.6	363.3			25909.4
BEV200 DM	2025	low	high	Small_SUV		54121.3	1799.0			225.4	270.1			21899.1
BEV200 DM	2030	low	high	Compact		38462.4	1438.0			173.4	196.2			15917.5
BEV200 DM	2030	low	high	Midsize		39537.0	1596.0			182.5	200.6			19614.6
BEV200 DM	2030	low	high	Midsize_SUV		59831.3	1847.0			241.3	305.0			22668.4
BEV200 DM	2030	low	high	Pickup		71350.1	2129.0			280.5	361.1			25002.6
BEV200 DM	2030	low	high	Small_SUV		52664.4	1761.0			218.7	268.3			21144.9
BEV200 DM	2045	low	high	Compact		36939.0	1376.0			165.3	188.5			14825.7
BEV200 DM	2045	low	high	Midsize		37238.4	1524.0			172.0	188.9			18428.4
BEV200 DM	2045	low	high	Midsize_SUV		57464.6	1758.0			230.6	293.3			21063.4
BEV200 DM	2045	low	high	Pickup		68565.9	2024.0			267.5	347.3			23144.0
BEV200 DM	2045	low	high	Small_SUV		49156.1	1675.0			204.4	250.4			19546.4
BEV300 DM	2010	low	high	Compact		66700.8	1854.0			210.1	223.7			30031.4
BEV300 DM	2010	low	high	Midsize		72016.1	2134.0			231.6	240.7			35169.8
BEV300 DM	2010	low	high	Midsize_SUV		101298.6	2523.0			296.9	339.2			43737.4
BEV300 DM	2010	low	high	Pickup		125712.9	2963.0			360.9	420.9			51292.6
BEV300 DM	2010	low	high	Small_SUV		86850.9	2372.0			266.0	293.1			39074.4
BEV300 DM	2015	low	high	Compact		64184.5	1787.0			199.6	216.4			28969.2
BEV300 DM	2015	low	high	Midsize		67993.0	1982.0			214.5	228.7			33591.0
BEV300 DM	2015	low	high	Midsize_SUV		96176.7	2338.0			275.0	323.0			41678.1
BEV300 DM	2015	low	high	Pickup		119043.0	2732.0			333.0	400.1			48728.5
BEV300 DM	2015	low	high	Small_SUV		83436.1	2201.0			246.7	279.5			37584.0
BEV300 DM	2020	low	high	Compact		66911.9	1714.0			203.5	226.5			23409.5
BEV300 DM	2020	low	high	Midsize		69587.5	1887.0			216.0	234.4			27570.7
BEV300 DM	2020	low	high	Midsize_SUV		91392.3	2192.0			262.5	306.6			31849.9

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
BEV300 DM	2020	low	high	Pickup		116757.0	2585.0			322.4	393.2			37278.7
BEV300 DM	2020	low	high	Small_SUV		85681.4	2101.0			249.1	287.3			30268.5
BEV300 DM	2025	low	high	Compact		65017.2	1583.0			191.1	217.6			20283.2
BEV300 DM	2025	low	high	Midsize		64213.9	1734.0			198.3	216.4			23719.6
BEV300 DM	2025	low	high	Midsize_SUV		90387.9	2020.0			249.7	304.2			27758.0
BEV300 DM	2025	low	high	Pickup		112492.8	2355.0			299.7	376.0			31709.0
BEV300 DM	2025	low	high	Small_SUV		83275.7	1932.0			234.5	279.7			26187.9
BEV300 DM	2030	low	high	Compact		58981.3	1528.0			197.2	204.8			18844.6
BEV300 DM	2030	low	high	Midsize		60576.1	1687.0			207.0	210.2			22617.6
BEV300 DM	2030	low	high	Midsize_SUV		91666.1	1987.0			276.8	315.5			27210.7
BEV300 DM	2030	low	high	Pickup		109475.2	2295.0			322.0	372.8			30437.7
BEV300 DM	2030	low	high	Small_SUV		80834.1	1884.0			251.0	277.7			25155.8
BEV300 DM	2045	low	high	Compact		56353.4	1447.0			187.1	195.6			17190.8
BEV300 DM	2045	low	high	Midsize		56766.0	1597.0			193.9	197.4			20807.7
BEV300 DM	2045	low	high	Midsize_SUV		87772.9	1871.0			262.8	301.9			24755.0
BEV300 DM	2045	low	high	Pickup		104716.0	2158.0			305.0	356.7			27543.6
BEV300 DM	2045	low	high	Small_SUV		75184.6	1772.0			233.6	258.4			22716.6
Conventional	2010	low	high	Compact	CI	0.0	1577.0	32.6	42.6					14782.6
Conventional	2010	low	high	Compact	SI	0.0	1516.0	30.0	43.6					11988.6
Conventional	2010	low	high	Midsize	CI	0.0	1823.0	30.7	40.9					18151.9
Conventional	2010	low	high	Midsize	SI	0.0	1768.0	27.5	40.4					15729.5
Conventional	2010	low	high	Midsize_SUV	CI	0.0	2014.0	27.8	34.2					19532.4
Conventional	2010	low	high	Midsize_SUV	SI	0.0	1989.0	23.0	32.0					16423.7
Conventional	2010	low	high	Pickup	CI	0.0	2289.0	24.6	29.0					20222.6
Conventional	2010	low	high	Pickup	SI	0.0	2270.0	19.8	27.1					17527.4

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
Conventional	2010	low	high	Small_SUV	CI	0.0	1949.0	28.8	36.1					17823.9
Conventional	2010	low	high	Small_SUV	SI	0.0	1899.0	25.5	35.6					15353.0
Conventional	2015	low	high	Compact	CI	0.0	1575.0	33.0	43.1					15069.4
Conventional	2015	low	high	Compact	SI	0.0	1515.0	30.4	44.3					12324.7
Conventional	2015	low	high	Midsize	CI	0.0	1754.0	31.7	41.9					18491.8
Conventional	2015	low	high	Midsize	SI	0.0	1698.0	28.6	41.9					15837.0
Conventional	2015	low	high	Midsize_SUV	CI	0.0	1943.0	28.8	35.1					19802.1
Conventional	2015	low	high	Midsize_SUV	SI	0.0	1914.0	24.0	33.2					16665.9
Conventional	2015	low	high	Pickup	CI	0.0	2201.0	25.5	29.9					20547.9
Conventional	2015	low	high	Pickup	SI	0.0	2183.0	20.7	28.0					17856.1
Conventional	2015	low	high	Small_SUV	CI	0.0	1871.0	29.7	37.0					18198.3
Conventional	2015	low	high	Small_SUV	SI	0.0	1819.0	26.5	36.8					15764.3
Conventional	2020	low	high	Compact	CI	0.0	1494.0	39.3	49.3					15630.1
Conventional	2020	low	high	Compact	SI	0.0	1441.0	34.0	46.1					13508.4
Conventional	2020	low	high	Midsize	CI	0.0	1664.0	37.3	47.9					18329.9
Conventional	2020	low	high	Midsize	SI	0.0	1612.0	32.2	44.2					16097.0
Conventional	2020	low	high	Midsize_SUV	CI	0.0	1848.0	33.4	40.9					18717.4
Conventional	2020	low	high	Midsize_SUV	SI	0.0	1819.0	28.0	36.6					16889.9
Conventional	2020	low	high	Pickup	CI	0.0	2097.0	29.3	33.8					20634.3
Conventional	2020	low	high	Pickup	SI	0.0	2080.0	24.0	30.1					17849.0
Conventional	2020	low	high	Small_SUV	CI	0.0	1773.0	34.6	41.6					18032.6
Conventional	2020	low	high	Small_SUV	SI	0.0	1726.0	29.9	38.7					15797.3
Conventional	2025	low	high	Compact	CI	0.0	1490.0	40.5	50.4					14479.0
Conventional	2025	low	high	Compact	SI	0.0	1436.0	39.9	52.8					13258.4
Conventional	2025	low	high	Midsize	CI	0.0	1658.0	38.7	50.0					18057.2

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
Conventional	2025	low	high	Midsize	SI	0.0	1608.0	38.0	51.8					16842.7
Conventional	2025	low	high	Midsize_SUV	CI	0.0	1842.0	34.1	40.5					18439.3
Conventional	2025	low	high	Midsize_SUV	SI	0.0	1812.0	33.0	41.3					17570.9
Conventional	2025	low	high	Pickup	CI	0.0	2089.0	30.0	34.2					20292.7
Conventional	2025	low	high	Pickup	SI	0.0	2069.0	28.5	34.4					18477.5
Conventional	2025	low	high	Small_SUV	CI	0.0	1767.0	35.4	41.7					17764.4
Conventional	2025	low	high	Small_SUV	SI	0.0	1721.0	34.8	43.6					16541.1
Conventional	2030	low	high	Compact	CI	0.0	1481.0	41.9	53.4					14233.0
Conventional	2030	low	high	Compact	SI	0.0	1427.0	43.2	58.5					13238.4
Conventional	2030	low	high	Midsize	CI	0.0	1647.0	40.4	53.3					17987.6
Conventional	2030	low	high	Midsize	SI	0.0	1596.0	41.6	58.2					16975.4
Conventional	2030	low	high	Midsize_SUV	CI	0.0	1830.0	34.2	39.8					18197.5
Conventional	2030	low	high	Midsize_SUV	SI	0.0	1800.0	34.8	42.8					17618.8
Conventional	2030	low	high	Pickup	CI	0.0	2075.0	30.6	34.6					19997.9
Conventional	2030	low	high	Pickup	SI	0.0	2054.0	30.5	36.7					18517.0
Conventional	2030	low	high	Small_SUV	CI	0.0	1754.0	36.1	42.5					17526.3
Conventional	2030	low	high	Small_SUV	SI	0.0	1708.0	37.2	46.6					16529.1
Conventional	2045	low	high	Compact	CI	0.0	1454.0	44.5	56.7					13917.6
Conventional	2045	low	high	Compact	SI	0.0	1402.0	46.3	62.6					12805.8
Conventional	2045	low	high	Midsize	CI	0.0	1616.0	43.2	57.6					17654.8
Conventional	2045	low	high	Midsize	SI	0.0	1564.0	45.0	63.3					16527.7
Conventional	2045	low	high	Midsize_SUV	CI	0.0	1791.0	37.0	43.4					17901.8
Conventional	2045	low	high	Midsize_SUV	SI	0.0	1745.0	39.0	48.3					17000.9
Conventional	2045	low	high	Pickup	CI	0.0	2028.0	33.6	37.1					18893.0
Conventional	2045	low	high	Pickup	SI	0.0	1992.0	34.8	41.1					18016.2

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
Conventional	2045	low	high	Small_SUV	CI	0.0	1720.0	38.7	46.0					17234.9
Conventional	2045	low	high	Small_SUV	SI	0.0	1673.0	40.4	51.1					16107.0
EREV PHEV50	2010	low	high	Compact	SI	17177.4	1999.0	43.4	47.4	247.0	260.1	231.1	235.1	28051.6
EREV PHEV50	2010	low	high	Midsize	SI	18727.6	2300.0	38.8	43.9	273.4	281.0	254.3	254.6	33081.0
EREV PHEV50	2010	low	high	Midsize_SUV	SI	23994.5	2603.0	30.2	34.5	332.0	377.2	315.6	337.8	36867.8
EREV PHEV50	2010	low	high	Pickup	SI	28594.2	3006.0	25.6	32.7	397.7	464.9	377.5	412.0	41602.4
EREV PHEV50	2010	low	high	Small_SUV	SI	21424.1	2482.0	33.3	39.2	301.7	330.9	285.1	296.9	34405.8
EREV PHEV50	2015	low	high	Compact	SI	16192.4	1921.0	49.3	51.7	227.9	247.3	215.6	222.8	24871.6
EREV PHEV50	2015	low	high	Midsize	SI	17261.1	2131.0	45.5	48.6	245.7	262.3	231.2	236.5	29220.5
EREV PHEV50	2015	low	high	Midsize_SUV	SI	22339.8	2420.0	35.0	36.2	303.9	355.1	289.3	316.5	32429.1
EREV PHEV50	2015	low	high	Pickup	SI	26762.8	2783.0	30.0	36.3	363.5	437.0	345.6	386.1	36334.9
EREV PHEV50	2015	low	high	Small_SUV	SI	19911.6	2301.0	38.9	41.0	274.0	310.5	261.1	278.2	30409.3
EREV PHEV50	2020	low	high	Compact	SI	16819.3	1762.0	48.9	49.8	232.8	259.3	216.5	227.8	21917.7
EREV PHEV50	2020	low	high	Midsize	SI	17590.4	1942.0	45.7	48.5	246.4	268.2	228.3	236.4	26088.9
EREV PHEV50	2020	low	high	Midsize_SUV	SI	21381.3	2176.0	37.1	38.0	290.6	337.1	270.3	295.3	27904.7
EREV PHEV50	2020	low	high	Pickup	SI	26300.5	2510.0	31.3	37.1	353.0	429.5	328.6	371.1	31000.8
EREV PHEV50	2020	low	high	Small_SUV	SI	20189.8	2089.0	39.4	40.4	275.4	316.9	256.7	277.3	26816.3
EREV PHEV50	2025	low	high	Compact	SI	16383.5	1712.0	52.9	55.1	223.8	252.6	203.6	217.2	18429.5
EREV PHEV50	2025	low	high	Midsize	SI	16785.0	1889.0	50.0	51.5	234.1	253.9	211.6	218.8	22173.8
EREV PHEV50	2025	low	high	Midsize_SUV	SI	21480.5	2129.0	39.4	38.4	287.2	342.2	260.5	291.3	23578.6
EREV PHEV50	2025	low	high	Pickup	SI	25930.1	2444.0	33.9	38.8	338.3	419.8	310.1	355.3	25645.9
EREV PHEV50	2025	low	high	Small_SUV	SI	20011.2	2039.0	41.9	41.8	270.0	314.3	244.8	269.3	22641.3
EREV PHEV50	2030	low	high	Compact	SI	15206.0	1663.0	60.0	59.7	209.2	232.0	183.9	193.3	17466.5
EREV PHEV50	2030	low	high	Midsize	SI	15860.2	1840.0	56.3	58.0	221.3	238.3	193.8	199.4	21237.9
EREV PHEV50	2030	low	high	Midsize_SUV	SI	21663.3	2089.0	42.6	40.1	284.3	346.8	251.7	285.5	22727.6

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EREV PHEV50	2030	low	high	Pickup	SI	25245.3	2386.0	37.9	38.7	327.6	409.9	291.1	335.2	24401.8
EREV PHEV50	2030	low	high	Small_SUV	SI	19373.2	1992.0	46.9	45.8	259.7	304.7	228.4	252.8	21676.0
EREV PHEV50	2045	low	high	Compact	SI	14637.0	1609.0	65.3	62.9	199.8	222.9	170.5	179.6	16893.9
EREV PHEV50	2045	low	high	Midsize	SI	15079.7	1777.0	62.0	62.2	209.5	225.1	177.7	182.5	20612.9
EREV PHEV50	2045	low	high	Midsize_SUV	SI	20969.1	2017.0	46.4	42.5	272.6	335.1	234.5	267.0	21934.9
EREV PHEV50	2045	low	high	Pickup	SI	24435.8	2304.0	41.4	37.5	314.6	395.8	271.1	313.4	23475.8
EREV PHEV50	2045	low	high	Small_SUV	SI	18350.6	1921.0	52.0	49.4	244.5	286.3	208.3	230.2	20900.5
FC Series HEV	2010	low	high	Compact		311.0	1662.0	92.6	93.4					18564.0
FC Series HEV	2010	low	high	Midsize		337.0	1937.0	82.5	86.4					22786.4
FC Series HEV	2010	low	high	Midsize_SUV		388.8	2207.0	65.3	61.3					24667.6
FC Series HEV	2010	low	high	Pickup		440.6	2537.0	54.4	49.7					26578.4
FC Series HEV	2010	low	high	Small_SUV		388.8	2121.0	72.0	70.7					23423.6
FC Series HEV	2015	low	high	Compact		285.1	1661.0	94.9	95.1					19322.2
FC Series HEV	2015	low	high	Midsize		337.0	1857.0	87.3	89.7					23490.5
FC Series HEV	2015	low	high	Midsize_SUV		362.9	2120.0	68.8	63.4					25317.1
FC Series HEV	2015	low	high	Pickup		414.7	2427.0	57.5	51.5					27336.4
FC Series HEV	2015	low	high	Small_SUV		362.9	2025.0	76.3	73.4					24061.3
FC Series HEV	2020	low	high	Compact		285.1	1562.0	98.5	94.6					19893.7
FC Series HEV	2020	low	high	Midsize		311.0	1745.0	91.2	91.0					24127.5
FC Series HEV	2020	low	high	Midsize_SUV		337.0	1979.0	75.3	69.3					25740.0
FC Series HEV	2020	low	high	Pickup		388.8	2273.0	62.1	54.3					28045.7
FC Series HEV	2020	low	high	Small_SUV		337.0	1901.0	79.6	74.3					24772.3
FC Series HEV	2025	low	high	Compact		518.4	1532.0	104.8	99.5					18099.3
FC Series HEV	2025	low	high	Midsize		570.2	1703.0	99.4	99.5					21973.9
FC Series HEV	2025	low	high	Midsize_SUV		673.9	1944.0	79.1	70.4					23466.9

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FC Series HEV	2025	low	high	Pickup		725.8	2225.0	66.3	57.2					25218.8
FC Series HEV	2025	low	high	Small_SUV		622.1	1861.0	84.4	76.9					22487.4
FC Series HEV	2030	low	high	Compact		777.6	1483.0	117.0	114.1					16737.9
FC Series HEV	2030	low	high	Midsize		855.4	1655.0	108.3	108.6					20666.9
FC Series HEV	2030	low	high	Midsize_SUV		933.1	1887.0	81.7	70.4					22131.0
FC Series HEV	2030	low	high	Pickup		1088.6	2167.0	70.1	59.5					23766.5
FC Series HEV	2030	low	high	Small_SUV		933.1	1816.0	88.2	78.8					21261.4
FC Series HEV	2045	low	high	Compact		907.2	1430.0	129.9	126.2					15907.7
FC Series HEV	2045	low	high	Midsize		997.9	1596.0	120.1	119.3					19824.3
FC Series HEV	2045	low	high	Midsize_SUV		1088.6	1821.0	89.5	76.4					21135.4
FC Series HEV	2045	low	high	Pickup		1179.4	2087.0	76.8	64.7					22617.7
FC Series HEV	2045	low	high	Small_SUV		997.9	1745.0	97.6	87.3					20194.2
Split HEV	2010	low	high	Compact	SI	233.3	1621.0	54.0	50.8					16055.8
Split HEV	2010	low	high	Midsize	SI	285.1	1891.0	47.8	46.7					20130.5
Split HEV	2010	low	high	Midsize_SUV	SI	311.0	2116.0	38.8	36.7					21159.3
Split HEV	2010	low	high	Pickup	SI	362.9	2429.0	32.0	30.2					22939.8
Split HEV	2010	low	high	Small_SUV	SI	311.0	2045.0	42.3	40.7					20344.1
Split HEV	2015	low	high	Compact	SI	233.3	1620.0	57.8	57.2					15662.5
Split HEV	2015	low	high	Midsize	SI	285.1	1813.0	53.3	53.2					19537.1
Split HEV	2015	low	high	Midsize_SUV	SI	311.0	2041.0	42.4	41.1					20443.3
Split HEV	2015	low	high	Pickup	SI	362.9	2339.0	35.4	33.9					22188.8
Split HEV	2015	low	high	Small_SUV	SI	285.1	1961.0	46.6	46.2					19691.9
Split HEV	2020	low	high	Compact	SI	233.3	1520.0	58.2	54.7					14901.5
Split HEV	2020	low	high	Midsize	SI	259.2	1698.0	53.6	53.0					18911.3
Split HEV	2020	low	high	Midsize_SUV	SI	285.1	1907.0	44.5	43.3					19647.4

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Split HEV	2020	low	high	Pickup	SI	337.0	2186.0	36.9	34.6					21268.9
Split HEV	2020	low	high	Small_SUV	SI	259.2	1834.0	46.9	45.8					18978.9
Split HEV	2025	low	high	Compact	SI	466.6	1500.0	61.2	59.3					14468.2
Split HEV	2025	low	high	Midsize	SI	518.4	1673.0	57.7	57.9					18201.4
Split HEV	2025	low	high	Midsize_SUV	SI	570.2	1881.0	46.7	44.4					18856.6
Split HEV	2025	low	high	Pickup	SI	673.9	2153.0	38.9	36.6					20286.1
Split HEV	2025	low	high	Small_SUV	SI	570.2	1807.0	49.7	47.8					18255.2
Split HEV	2030	low	high	Compact	SI	622.1	1479.0	70.2	68.1					14364.1
Split HEV	2030	low	high	Midsize	SI	699.8	1644.0	66.4	64.7					17792.5
Split HEV	2030	low	high	Midsize_SUV	SI	1010.9	1856.0	51.3	46.6					18842.6
Split HEV	2030	low	high	Pickup	SI	1166.4	2120.0	43.8	39.9					19943.3
Split HEV	2030	low	high	Small_SUV	SI	933.1	1782.0	56.1	52.4					18175.7
Split HEV	2045	low	high	Compact	SI	725.8	1440.0	76.6	72.6					14391.4
Split HEV	2045	low	high	Midsize	SI	816.5	1600.0	72.9	69.8					17818.2
Split HEV	2045	low	high	Midsize_SUV	SI	1088.6	1799.0	55.4	49.4					18690.7
Split HEV	2045	low	high	Pickup	SI	1360.8	2057.0	47.8	42.1					19860.2
Split HEV	2045	low	high	Small_SUV	SI	997.9	1727.0	61.7	57.0					18031.9
Split PHEV25	2010	low	high	Compact	SI	8340.9	1823.0	53.1	48.7	232.0	242.7	161.7	163.3	21192.0
Split PHEV25	2010	low	high	Midsize	SI	9199.9	2125.0	47.1	43.9	250.9	265.4	177.6	178.7	25722.2
Split PHEV25	2010	low	high	Midsize_SUV	SI	12154.6	2422.0	36.8	34.3	332.3	360.6	233.9	243.1	28942.8
Split PHEV25	2010	low	high	Pickup	SI	14616.8	2776.0	30.4	28.6	398.0	452.5	281.0	296.6	32064.7
Split PHEV25	2010	low	high	Small_SUV	SI	10800.3	2300.0	41.3	38.8	297.1	314.7	208.9	212.8	27191.0
Split PHEV25	2015	low	high	Compact	SI	8030.7	1800.0	58.0	54.3	212.7	233.0	152.0	156.8	20147.5
Split PHEV25	2015	low	high	Midsize	SI	8649.6	2004.0	53.3	50.7	230.5	249.4	164.7	167.6	24267.5
Split PHEV25	2015	low	high	Midsize_SUV	SI	11536.1	2275.0	41.8	39.1	313.6	339.7	221.4	229.9	26850.1

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
Split PHEV25	2015	low	high	Pickup	SI	14968.8	2626.0	34.3	32.2	373.8	422.9	277.5	291.6	30010.7
Split PHEV25	2015	low	high	Small_SUV	SI	10186.9	2172.0	46.2	44.2	282.6	296.4	197.0	200.5	25112.1
Split PHEV25	2020	low	high	Compact	SI	8192.4	1642.0	59.2	53.3	221.0	242.4	153.2	159.1	18341.9
Split PHEV25	2020	low	high	Midsize	SI	8620.3	1845.0	54.6	51.0	239.5	250.3	163.3	165.0	22862.7
Split PHEV25	2020	low	high	Midsize_SUV	SI	10862.6	2078.0	44.6	41.7	290.2	320.6	202.9	211.8	24494.1
Split PHEV25	2020	low	high	Pickup	SI	13457.9	2386.0	36.7	33.4	352.2	417.7	249.7	267.4	27164.0
Split PHEV25	2020	low	high	Small_SUV	SI	10199.6	1993.0	47.3	44.2	275.2	300.0	191.0	198.2	23544.8
Split PHEV25	2025	low	high	Compact	SI	7974.0	1614.0	63.2	57.5	214.7	234.4	145.3	150.4	15996.9
Split PHEV25	2025	low	high	Midsize	SI	8209.7	1789.0	59.6	56.3	227.4	237.9	151.5	152.5	19723.4
Split PHEV25	2025	low	high	Midsize_SUV	SI	10936.9	2018.0	47.5	43.1	286.0	331.3	196.7	209.0	20814.4
Split PHEV25	2025	low	high	Pickup	SI	13264.7	2310.0	39.4	35.6	343.1	410.2	237.4	256.2	22621.8
Split PHEV25	2025	low	high	Small_SUV	SI	10114.8	1935.0	50.8	46.6	267.4	304.7	183.0	192.1	20024.4
Split PHEV25	2030	low	high	Compact	SI	7379.3	1579.0	73.3	66.6	201.0	216.4	130.8	133.9	15464.5
Split PHEV25	2030	low	high	Midsize	SI	7729.4	1752.0	68.5	64.2	204.5	223.8	134.8	138.8	19184.9
Split PHEV25	2030	low	high	Midsize_SUV	SI	10958.3	1982.0	52.5	45.6	285.7	338.6	189.8	204.3	20252.5
Split PHEV25	2030	low	high	Pickup	SI	12921.3	2263.0	44.6	39.0	324.9	400.6	223.1	241.8	21888.4
Split PHEV25	2030	low	high	Small_SUV	SI	9751.9	1897.0	57.7	51.2	256.9	294.5	170.4	180.0	19416.3
Split PHEV25	2045	low	high	Compact	SI	7088.2	1533.0	79.7	71.2	191.4	208.6	120.8	124.3	15216.9
Split PHEV25	2045	low	high	Midsize	SI	7328.7	1699.0	75.3	70.1	202.6	212.0	126.4	126.7	18907.7
Split PHEV25	2045	low	high	Midsize_SUV	SI	10597.1	1919.0	57.0	48.3	276.1	329.1	176.5	190.8	19857.2
Split PHEV25	2045	low	high	Pickup	SI	12547.4	2189.0	48.7	41.3	315.2	389.9	207.9	226.4	21128.0
Split PHEV25	2045	low	high	Small_SUV	SI	9185.1	1834.0	63.8	56.0	242.1	276.9	154.7	163.2	19027.2
BEV100 DM	2020	high	low	Compact		16527.2	1313.0			143.1	162.2			13398.6
BEV100 DM	2020	high	low	Midsize		17890.2	1467.0			156.2	178.1			17225.3
BEV100 DM	2020	high	low	Midsize_SUV		25626.0	1661.0			198.3	251.4			18628.0

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BEV100 DM	2020	high	low	Pickup		31015.4	1907.0			235.3	306.4			20243.4
BEV100 DM	2020	high	low	Small_SUV		20875.3	1586.0			173.1	205.6			17380.0
BEV100 DM	2025	high	low	Compact		16678.4	1253.0			141.1	163.5			12962.6
BEV100 DM	2025	high	low	Midsize		16749.5	1394.0			147.8	165.7			16622.0
BEV100 DM	2025	high	low	Midsize_SUV		24899.9	1572.0			191.2	244.3			17856.4
BEV100 DM	2025	high	low	Pickup		30521.5	1814.0			228.9	301.8			19502.4
BEV100 DM	2025	high	low	Small_SUV		21088.8	1508.0			170.5	208.1			16869.0
BEV100 DM	2030	high	low	Compact		16288.1	1204.0			139.2	160.0			13003.2
BEV100 DM	2030	high	low	Midsize		14793.4	1332.0			138.8	145.6			16530.4
BEV100 DM	2030	high	low	Midsize_SUV		23978.6	1506.0			187.5	236.2			17887.1
BEV100 DM	2030	high	low	Pickup		36387.9	1748.0			226.8	299.7			20254.9
BEV100 DM	2030	high	low	Small_SUV		19657.1	1443.0			163.4	194.2			16847.1
BEV100 DM	2045	high	low	Compact		12296.3	1078.0			118.0	120.3			13112.4
BEV100 DM	2045	high	low	Midsize		13531.2	1196.0			128.0	132.8			17108.3
BEV100 DM	2045	high	low	Midsize_SUV		22250.6	1351.0			173.4	219.0			18427.8
BEV100 DM	2045	high	low	Pickup		28359.8	1552.0			210.0	280.5			20276.9
BEV100 DM	2045	high	low	Small_SUV		18178.5	1294.0			151.2	179.4			17435.3
BEV200 DM	2020	high	low	Compact		33157.7	1389.0			148.6	166.2			15940.7
BEV200 DM	2020	high	low	Midsize		36354.2	1551.0			162.2	182.6			20047.5
BEV200 DM	2020	high	low	Midsize_SUV		51555.3	1780.0			206.7	258.7			22590.4
BEV200 DM	2020	high	low	Pickup		63476.9	2056.0			245.9	315.8			25202.6
BEV200 DM	2020	high	low	Small_SUV		42427.0	1685.0			180.0	211.1			20675.0
BEV200 DM	2025	high	low	Compact		33718.3	1310.0			145.3	167.0			15034.5
BEV200 DM	2025	high	low	Midsize		33833.2	1451.0			152.1	168.9			18699.9
BEV200 DM	2025	high	low	Midsize_SUV		50369.9	1658.0			197.4	250.4			20952.6

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BEV200 DM	2025	high	low	Pickup		61859.6	1910.0			235.7	308.5			23204.1
BEV200 DM	2025	high	low	Small_SUV		42677.3	1582.0			175.8	212.8			19493.8
BEV200 DM	2030	high	low	Compact		32887.0	1258.0			140.7	167.0			14932.7
BEV200 DM	2030	high	low	Midsize		29994.9	1382.0			139.5	151.7			18298.0
BEV200 DM	2030	high	low	Midsize_SUV		48081.2	1584.0			191.5	245.8			20689.1
BEV200 DM	2030	high	low	Pickup		60714.9	1828.0			232.8	308.7			23089.1
BEV200 DM	2030	high	low	Small_SUV		39747.7	1509.0			165.5	202.6			19183.1
BEV200 DM	2045	high	low	Compact		24880.2	1119.0			118.5	125.3			14383.8
BEV200 DM	2045	high	low	Midsize		27416.8	1242.0			128.6	138.4			18511.4
BEV200 DM	2045	high	low	Midsize_SUV		44551.0	1423.0			177.1	227.7			20680.7
BEV200 DM	2045	high	low	Pickup		57054.7	1638.0			215.8	290.7			23123.0
BEV200 DM	2045	high	low	Small_SUV		36750.5	1355.0			153.1	187.2			19311.4
BEV300 DM	2020	high	low	Compact		50834.5	1471.0			153.1	172.3			18642.2
BEV300 DM	2020	high	low	Midsize		55681.1	1640.0			167.1	189.2			23000.3
BEV300 DM	2020	high	low	Midsize_SUV		79010.8	1907.0			214.2	267.4			26786.6
BEV300 DM	2020	high	low	Pickup		97465.5	2212.0			255.8	326.4			30394.5
BEV300 DM	2020	high	low	Small_SUV		65170.9	1789.0			185.8	218.7			24148.2
BEV300 DM	2025	high	low	Compact		51336.5	1370.0			148.4	171.9			17176.1
BEV300 DM	2025	high	low	Midsize		51539.7	1511.0			155.3	174.0			20853.3
BEV300 DM	2025	high	low	Midsize_SUV		76749.5	1748.0			202.6	257.0			24159.4
BEV300 DM	2025	high	low	Pickup		94463.1	2020.0			242.6	316.4			27165.4
BEV300 DM	2025	high	low	Small_SUV		65045.3	1658.0			179.9	218.9			22214.2
BEV300 DM	2030	high	low	Compact		49974.1	1314.0			160.3	172.7			16918.5
BEV300 DM	2030	high	low	Midsize		45534.5	1432.0			156.0	159.3			20104.9
BEV300 DM	2030	high	low	Midsize_SUV		73104.6	1666.0			218.7	252.5			23597.6

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BEV300 DM	2030	high	low	Pickup		92616.4	1931.0			265.4	316.1			26794.0
BEV300 DM	2030	high	low	Small_SUV		60501.3	1577.0			189.5	209.1			21595.9
BEV300 DM	2045	high	low	Compact		37754.3	1161.0			131.8	131.5			15684.2
BEV300 DM	2045	high	low	Midsize		41590.2	1288.0			143.5	145.2			19943.2
BEV300 DM	2045	high	low	Midsize_SUV		67670.6	1497.0			201.7	233.6			23015.7
BEV300 DM	2045	high	low	Pickup		86876.4	1734.0			245.3	297.2			26131.3
BEV300 DM	2045	high	low	Small_SUV		55913.8	1417.0			175.0	192.9			21246.6
Conventional	2020	high	low	Compact	CI	0.0	1441.0	50.3	64.6					14163.8
Conventional	2020	high	low	Compact	SI	0.0	1388.0	44.0	62.8					12729.8
Conventional	2020	high	low	Midsize	CI	0.0	1601.0	46.6	60.0					17797.3
Conventional	2020	high	low	Midsize	SI	0.0	1549.0	40.6	57.7					16361.3
Conventional	2020	high	low	Midsize_SUV	CI	0.0	1773.0	41.1	49.4					18058.4
Conventional	2020	high	low	Midsize_SUV	SI	0.0	1726.0	36.2	48.1					16894.4
Conventional	2020	high	low	Pickup	CI	0.0	2007.0	36.9	41.5					19081.4
Conventional	2020	high	low	Pickup	SI	0.0	1968.0	32.0	39.9					17946.6
Conventional	2020	high	low	Small_SUV	CI	0.0	1704.0	44.9	55.9					17525.6
Conventional	2020	high	low	Small_SUV	SI	0.0	1656.0	39.0	53.7					16097.8
Conventional	2025	high	low	Compact	CI	0.0	1406.0	53.7	67.9					14704.2
Conventional	2025	high	low	Compact	SI	0.0	1353.0	51.1	69.9					13777.4
Conventional	2025	high	low	Midsize	CI	0.0	1559.0	50.6	66.3					18422.2
Conventional	2025	high	low	Midsize	SI	0.0	1507.0	48.1	67.7					17478.9
Conventional	2025	high	low	Midsize_SUV	CI	0.0	1727.0	44.4	53.3					18816.9
Conventional	2025	high	low	Midsize_SUV	SI	0.0	1679.0	42.6	54.1					18135.0
Conventional	2025	high	low	Pickup	CI	0.0	1951.0	39.7	44.4					19992.9
Conventional	2025	high	low	Pickup	SI	0.0	1912.0	37.6	44.7					19337.9

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Conventional	2025	high	low	Small_SUV	CI	0.0	1659.0	48.0	58.6					18233.9
Conventional	2025	high	low	Small_SUV	SI	0.0	1611.0	45.2	59.0					17305.8
Conventional	2030	high	low	Compact	CI	0.0	1366.0	56.3	70.7					14543.6
Conventional	2030	high	low	Compact	SI	0.0	1312.0	56.3	75.7					13456.7
Conventional	2030	high	low	Midsize	CI	0.0	1512.0	54.3	73.5					18273.3
Conventional	2030	high	low	Midsize	SI	0.0	1458.0	54.1	78.1					17170.8
Conventional	2030	high	low	Midsize_SUV	CI	0.0	1671.0	47.6	55.4					18700.7
Conventional	2030	high	low	Midsize_SUV	SI	0.0	1620.0	47.8	58.8					17563.7
Conventional	2030	high	low	Pickup	CI	0.0	1887.0	41.4	46.3					19774.4
Conventional	2030	high	low	Pickup	SI	0.0	1847.0	41.1	48.1					18946.6
Conventional	2030	high	low	Small_SUV	CI	0.0	1606.0	51.3	63.5					18071.6
Conventional	2030	high	low	Small_SUV	SI	0.0	1557.0	50.4	66.0					16974.1
Conventional	2045	high	low	Compact	CI	0.0	1258.0	64.3	87.2					14833.1
Conventional	2045	high	low	Compact	SI	0.0	1201.0	64.7	94.6					13902.9
Conventional	2045	high	low	Midsize	CI	0.0	1388.0	59.6	81.0					18744.7
Conventional	2045	high	low	Midsize	SI	0.0	1331.0	60.1	87.2					17796.9
Conventional	2045	high	low	Midsize_SUV	CI	0.0	1529.0	53.1	61.3					19288.6
Conventional	2045	high	low	Midsize_SUV	SI	0.0	1476.0	53.2	65.6					18326.0
Conventional	2045	high	low	Pickup	CI	0.0	1717.0	46.1	50.4					20579.1
Conventional	2045	high	low	Pickup	SI	0.0	1673.0	46.0	53.3					19875.8
Conventional	2045	high	low	Small_SUV	CI	0.0	1470.0	56.6	69.8					18632.2
Conventional	2045	high	low	Small_SUV	SI	0.0	1417.0	56.2	73.6					17693.9
EREV PHEV50	2020	high	low	Compact	SI	12565.0	1611.0	81.5	74.8	170.6	193.4	149.1	159.0	17288.9
EREV PHEV50	2020	high	low	Midsize	SI	13792.4	1790.0	73.1	68.6	187.2	212.7	163.2	174.7	21331.7
EREV PHEV50	2020	high	low	Midsize_SUV	SI	17974.3	2016.0	56.7	51.1	232.6	290.6	205.0	235.8	22704.3

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EREV PHEV50	2020	high	low	Pickup	SI	21469.7	2306.0	49.1	42.4	274.6	353.1	242.9	284.5	24614.4
EREV PHEV50	2020	high	low	Small_SUV	SI	15310.5	1915.0	64.8	60.9	205.5	239.5	178.7	196.3	21426.4
EREV PHEV50	2025	high	low	Compact	SI	12698.4	1544.0	84.8	74.9	170.2	195.2	145.0	156.5	16734.2
EREV PHEV50	2025	high	low	Midsize	SI	13159.2	1706.0	79.4	76.9	178.0	199.7	152.0	160.5	20542.1
EREV PHEV50	2025	high	low	Midsize_SUV	SI	17675.7	1918.0	62.2	52.6	225.1	283.3	194.5	224.6	21614.7
EREV PHEV50	2025	high	low	Pickup	SI	21240.5	2191.0	52.8	43.4	266.4	347.3	231.5	273.3	23272.3
EREV PHEV50	2025	high	low	Small_SUV	SI	15467.3	1830.0	69.2	60.6	202.3	242.7	173.4	193.6	20645.4
EREV PHEV50	2030	high	low	Compact	SI	12131.7	1469.0	92.3	80.3	161.7	187.6	137.5	150.4	16509.5
EREV PHEV50	2030	high	low	Midsize	SI	11639.1	1610.0	90.5	86.2	159.7	173.7	136.0	140.3	20301.6
EREV PHEV50	2030	high	low	Midsize_SUV	SI	16901.6	1822.0	66.3	56.9	215.2	272.0	186.0	215.1	21037.2
EREV PHEV50	2030	high	low	Pickup	SI	20692.9	2080.0	57.0	46.2	258.2	338.9	224.9	266.8	22659.8
EREV PHEV50	2030	high	low	Small_SUV	SI	14328.7	1734.0	75.8	67.7	187.4	223.2	160.7	179.0	20183.7
EREV PHEV50	2045	high	low	Compact	SI	9792.9	1309.0	108.6	114.4	135.3	143.7	113.2	114.8	16319.1
EREV PHEV50	2045	high	low	Midsize	SI	10710.9	1446.0	103.2	106.0	146.7	158.3	123.2	126.3	20446.8
EREV PHEV50	2045	high	low	Midsize_SUV	SI	15723.7	1627.0	77.3	68.5	197.4	251.9	169.2	196.3	21193.0
EREV PHEV50	2045	high	low	Pickup	SI	19453.7	1850.0	67.1	61.7	237.0	320.7	205.0	246.0	22945.3
EREV PHEV50	2045	high	low	Small_SUV	SI	13294.8	1550.0	89.4	82.4	172.6	205.9	146.2	163.0	20389.8
FC Series HEV	2020	high	low	Compact		518.4	1447.0	126.7	121.6					16578.5
FC Series HEV	2020	high	low	Midsize		570.2	1618.0	114.8	110.3					20573.9
FC Series HEV	2020	high	low	Midsize_SUV		622.1	1837.0	90.2	77.8					21720.0
FC Series HEV	2020	high	low	Pickup		673.9	2106.0	75.6	63.8					23350.3
FC Series HEV	2020	high	low	Small_SUV		570.2	1750.0	102.8	95.2					20660.2
FC Series HEV	2025	high	low	Compact		699.8	1379.0	134.2	124.4					15823.9
FC Series HEV	2025	high	low	Midsize		777.6	1533.0	126.4	122.2					19698.1
FC Series HEV	2025	high	low	Midsize_SUV		855.4	1741.0	97.1	82.5					20805.4

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
FC Series HEV	2025	high	low	Pickup		1010.9	2002.0	81.0	66.9					22419.3
FC Series HEV	2025	high	low	Small_SUV		855.4	1669.0	108.5	96.6					19965.0
FC Series HEV	2030	high	low	Compact		933.1	1300.0	158.7	152.3					15262.4
FC Series HEV	2030	high	low	Midsize		1036.8	1447.0	149.5	147.4					19060.5
FC Series HEV	2030	high	low	Midsize_SUV		1140.5	1641.0	108.7	91.1					20229.7
FC Series HEV	2030	high	low	Pickup		1244.2	1884.0	89.1	72.4					21800.1
FC Series HEV	2030	high	low	Small_SUV		1036.8	1570.0	125.6	110.5					19188.3
FC Series HEV	2045	high	low	Compact		933.1	1140.0	185.7	177.7					15145.2
FC Series HEV	2045	high	low	Midsize		933.1	1262.0	172.9	168.9					19136.2
FC Series HEV	2045	high	low	Midsize_SUV		1049.8	1421.0	125.8	102.4					20110.1
FC Series HEV	2045	high	low	Pickup		1166.4	1631.0	102.4	79.7					21814.5
FC Series HEV	2045	high	low	Small_SUV		1049.8	1363.0	145.2	125.1					19304.8
Split HEV	2020	high	low	Compact	SI	414.7	1443.0	84.2	83.9					14020.6
Split HEV	2020	high	low	Midsize	SI	466.6	1611.0	76.8	75.8					17800.9
Split HEV	2020	high	low	Midsize_SUV	SI	518.4	1805.0	61.3	57.2					18355.9
Split HEV	2020	high	low	Pickup	SI	622.1	2062.0	51.5	47.5					19515.2
Split HEV	2020	high	low	Small_SUV	SI	518.4	1731.0	68.9	67.7					17720.2
Split HEV	2025	high	low	Compact	SI	622.1	1394.0	88.6	84.3					14452.7
Split HEV	2025	high	low	Midsize	SI	699.8	1552.0	83.2	81.1					18236.6
Split HEV	2025	high	low	Midsize_SUV	SI	777.6	1738.0	65.8	59.5					18744.8
Split HEV	2025	high	low	Pickup	SI	933.1	1984.0	55.2	49.2					19938.5
Split HEV	2025	high	low	Small_SUV	SI	699.8	1668.0	72.6	68.1					18099.6
Split HEV	2030	high	low	Compact	SI	933.1	1349.0	98.2	92.2					14663.2
Split HEV	2030	high	low	Midsize	SI	933.1	1490.0	96.2	95.6					18369.7
Split HEV	2030	high	low	Midsize_SUV	SI	1244.2	1673.0	72.4	65.7					19037.5

Vehicle Powertrain:	Lab Year:	Technology Progress:	Technology Cost:	Vehicle Class:	Engine Fuel Type	Battery Usable Energy End of Life: {Wh}	Vehicle Test Weight: {Kg}	Unadjusted Fuel Economy CS on UDDS (Gas. Equivalent): {mile/gallon}	Unadjusted Fuel Economy CS on HWFET (Gas. Equivalent): {mile/gallon}	Unadjusted Electrical Energy Consumption CD on UDDS : {W.h/mile}	Unadjusted Electrical Energy Consumption CD on HWFET : {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on UDDS: {W.h/mile}	Utility-weighted Unadjusted PHEV Electrical Consumption on HWFET: {W.h/mile}	Vehicle Manufacturing Cost (2015$)
Split HEV	2030	high	low	Pickup	SI	1658.9	1909.0	60.5	53.1					20377.3
Split HEV	2030	high	low	Small_SUV	SI	1244.2	1606.0	81.5	78.0					18435.0
Split HEV	2045	high	low	Compact	SI	1516.3	1231.0	126.8	129.8					15106.4
Split HEV	2045	high	low	Midsize	SI	1283.0	1355.0	114.7	115.6					18903.2
Split HEV	2045	high	low	Midsize_SUV	SI	2099.5	1521.0	87.4	78.4					19866.4
Split HEV	2045	high	low	Pickup	SI	2099.5	1719.0	72.5	62.5					21169.8
Split HEV	2045	high	low	Small_SUV	SI	1866.2	1457.0	99.3	94.1					19120.6
Split PHEV25	2020	high	low	Compact	SI	6376.9	1544.0	89.4	81.7	173.8	186.5	112.0	114.1	15813.8
Split PHEV25	2020	high	low	Midsize	SI	7031.2	1717.0	80.9	73.9	191.8	205.1	123.6	125.7	19742.2
Split PHEV25	2020	high	low	Midsize_SUV	SI	9449.5	1933.0	63.4	55.7	247.3	291.7	162.4	173.6	20933.9
Split PHEV25	2020	high	low	Pickup	SI	11497.6	2208.0	52.8	46.2	289.6	354.3	196.2	212.0	22608.5
Split PHEV25	2020	high	low	Small_SUV	SI	7997.3	1844.0	71.8	66.2	216.4	233.8	139.9	144.0	19861.1
Split PHEV25	2025	high	low	Compact	SI	6517.5	1470.0	92.8	82.8	172.6	191.7	109.3	114.1	15193.5
Split PHEV25	2025	high	low	Midsize	SI	6789.4	1628.0	86.8	79.8	182.4	197.6	115.1	117.5	18959.6
Split PHEV25	2025	high	low	Midsize_SUV	SI	9371.1	1841.0	67.7	58.2	237.4	291.7	154.2	168.0	19843.3
Split PHEV25	2025	high	low	Pickup	SI	11372.3	2091.0	56.6	48.2	284.4	363.9	185.9	205.8	21204.6
Split PHEV25	2025	high	low	Small_SUV	SI	8154.4	1759.0	75.3	67.0	213.6	246.4	135.9	144.2	19036.3
Split PHEV25	2030	high	low	Compact	SI	6156.4	1419.0	103.8	91.1	163.1	184.2	103.3	107.9	15129.8
Split PHEV25	2030	high	low	Midsize	SI	5960.6	1566.0	101.5	96.5	164.8	170.6	102.5	101.7	18869.5
Split PHEV25	2030	high	low	Midsize_SUV	SI	8905.6	1763.0	75.2	64.6	228.3	275.6	147.2	159.0	19718.2
Split PHEV25	2030	high	low	Pickup	SI	11086.6	2009.0	62.3	52.2	277.3	349.3	181.6	199.6	21121.0
Split PHEV25	2030	high	low	Small_SUV	SI	7487.6	1684.0	85.9	77.1	198.1	223.2	125.6	131.4	18920.9
Split PHEV25	2045	high	low	Compact	SI	4937.0	1277.0	131.7	129.5	135.1	138.4	83.2	82.5	15175.6
Split PHEV25	2045	high	low	Midsize	SI	5457.4	1411.0	122.6	119.1	149.1	153.3	91.8	91.3	19169.9
Split PHEV25	2045	high	low	Midsize_SUV	SI	8167.2	1582.0	91.2	77.6	203.9	258.3	132.4	144.4	20023.4

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Split PHEV25	2045	high	low	Pickup	SI	10209.2	1794.0	75.5	61.8	253.3	326.5	163.8	182.6	21591.5
Split PHEV25	2045	high	low	Small_SUV	SI	6870.3	1512.0	102.9	93.1	178.9	207.3	112.8	119.1	19225.9

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